European Science and Technology Observatory

On Science and Precaution

in the Management of Technological Risk

Volume II

Case studies

EUROPEAN COMMISSION
JOINT RESEARCH CENTRE

Report EUR 19056/EN/2

Institute for Prospective Technological Studies

About the JRC-IPTS

The **Joint Research Centre** (JRC) is a Directorate General of the European Commission, staffed with approximately 2,100 people, coming in the vast majority from the 15 Member States of the European Union. The Brussels Support Services (including the office of the Director General and the Science Strategy Directorate) and seven Institutes Institutes located in five different countries compose the main organisational structure of the JRC (http//:www.jrc.org). The **mission of the JRC** is to provide customer-driven scientific and technical support for the conception, implementation and monitoring of EU policies.

The Institute for Prospective Technological Studies (IPTS) is one of the seven Institutes making up the JRC. It was established in Seville, Spain, in September 1994.

The **mission of the IPTS** is to provide prospective techno-economic analyses in support of the European policy-making process. IPTS' prime objectives are to monitor and analyse science and technology developments, their cross-sectoral impact, and their inter-relationship with the socio-economic context and their implications for future policy development. IPTS operates international networks, pools the expertise of high level advisors, and presents information in a timely and synthetic fashion to policy makers (http//:www.jrc.es).

The **IPTS is a unique public advisory body**, independent from special national or commercial interests, closely associated with the EU policy-making process. In fact, most of the work undertaken by the IPTS is in response to direct requests from (or takes the form of long-term policy support on behalf of) the European Commission Directorate Generals, or European Parliament Committees. The IPTS also does work for Member States' governmental, academic or industrial organisations, though this represents a minor share of its total activities.

Although particular emphasis is placed on **key Science and Technology fields**, especially those that have a driving role and even the potential to reshape our society, important efforts are devoted to improving the understanding of the complex interactions between technology, economy and society. Indeed, the impact of technology on society and, conversely, the way technological development is driven by societal changes, are **highly relevant themes within the European decision-making context**.

The **inter-disciplinary prospective approach** adopted by the Institute is intended to provide European decision-makers with a deeper understanding of the emerging science and technology issues, and it complements the activities undertaken by other institutes of the Joint Research Centre.

The IPTS **approach** is to collect information about technological developments and their application in Europe and the world, analyse this information and transmit it in an accessible form to European decision-makers. This is implemented in the following **sectors of activity**:

- Technologies for Sustainable Development
- Life Sciences / Information and Communication Technologies
- Technology, Employment, Competitiveness and Society
- Futures project

In order to implement its mission, the Institute develops appropriate contacts, awareness and skills to anticipate and follow the agenda of the policy decision-makers. **IPTS Staff** is a mix of highly experienced engineers, scientists (life-, social- material- etc.) and economists. Cross-disciplinary experience is a necessary asset. The IPTS success is also based on its **networking capabilities and the quality of its networks** as enabling sources of relevant information. In fact, in addition to its own resources, the IPTS makes use of external Advisory Groups and operates a number of formal or informal networks. The most important is a Network of European Institutes (*the European Science and Technology Observatory*) working in similar areas. These networking activities enable the IPTS to draw on a large pool of available expertise, while allowing a continuous process of external peer-review of the in-house activities.

About ESTO

The European Science and Technology Observatory (ESTO) is a network of organisations operating as a virtual institute under the European Commission's – Joint Research Centre's (JRC's) Institute for Prospective Technological Studies (IPTS) - leadership and funding. The European Commission JRC-IPTS formally constituted, following a brief pilot period, the European Science and Technology Observatory (ESTO) in 1997. After a call for tender, the second formal contract for ESTO started on May 1st 2001 for a period of 5 years.

Today, **ESTO is composed of twenty European institutions**, all with experience in the field of scientific and technological foresight, forecasting or assessment at the national level. These nineteen organisations have a formal obligation towards the IPTS and are the nucleus of a far larger network. Membership is being continuously reviewed and expanded with a view to match the evolving needs of the IPTS and to incorporate new competent organisations from both inside and outside of the EU.
In line with the objective of supporting the JRC-IPTS work, ESTO **aims** at detecting, at an early stage, scientific or technological breakthroughs, trends and events of potential socio-economic importance, which may require action at a European decision-making level.

The ESTO **core-competence** therefore resides in prospective analysis and advice on S&T changes relevant to EU society, economy and policy.

The **main customers** for these activities are European science and technology policy-makers, in particular within the European Commission and Parliament. ESTO also recognises and addresses the role of a much wider community, such as policy-making circles in the Member States and decision-makers in both non-governmental organisations and industry.

ESTO members, therefore, **share the responsibility** of supplying the IPTS with up-to-date and high quality scientific and technological information drawn from all over the world, facilitated by the network's broad presence and linkages, including access to relevant knowledge within the JRC' Institutes.

Currently, ESTO is engaged in the following **main activities:**

- A series of **Specific Studies**, These studies, usually consist in comparing the situation, practices and/or experiences in various member states, and can be of a different nature a) *Anticipation/Prospective analysis*, intended to act as a trigger for in-depth studies of European foresight nature, aiming at the identification and description of trends rather than static situations; b) *Direct support of policies in preparation* (ex-ante analysis); and c) *Direct support of policies in action* (ex-post analysis, anticipating future developments).
- Implementation of **Fast-Track** actions to provide quick responses to specific S&T assessment queries. On the other hand, they can precede or complement the above mentioned Specific Studies.
- To produce input to **Longer-Term Monitoring Activities** that serves as a basis of experience and information for all other tasks. The monitoring is executed with a focus on certain topics that are of primary interest for the majority of ESTO organisations as well as for the IPTS and the EU.
- ESTO develops a permanent **Technology Watch** function achieved by means of a set of **thematic networks** providing input into a database on technology watch events and analysis. These actions are putting ESTO and JRC-IPTS in the position to be able to provide rapid responses to specific requests from European decision-makers.
- Support the production of **"The IPTS Report"**, a monthly journal targeted at European policy-makers and containing articles on science and technology developments, either not yet on the policy-makers' agenda, but likely to emerge there sooner or later, or on aspects of such developments that have not yet been fully appreciated.
- Organisation of a number of **meetings, workshops and conferences** of various sizes and of flexible organisational structure on specific and highly policy relevant topics which bring together experts to elaborate on these topics.
- The **extension of the ESTO network** beyond the original members – according to the scope and quality parameters - and involvement of these in ESTO activities. This includes the objective to broaden the operation of the ESTO network to include relevant partners from EU Candidate Countries.

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On Science and Precaution

in the Management of Technological Risk

An ESTO Project Report

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European Commission - JRC
Institute Prospective Technological Studies
Seville

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This project has been carried out upon request of the European Commission's Forward Studies Unit (presently the Group of Policy Advisers) and in the framework of an agreement between the JRC-IPTS and the Forward Studies Unit

November 2001

EUR 19056/EN/2

Printed in Spain

Prologue

This study co-ordinated by Dr. Stirling shows how greatly our thinking has changed on issues of the management of risks. The use of sophisticated scientific methods in the assessment and then management of risks began with the problems of major industrial hazards, notably those of nuclear power. At first it was believed that quantitative techniques, either of statistics or of modeling, would suffice for the guidance of risk policy and risk management. But as experience accumulated, it became clear that while science is an essential core of the assessment process, it could not be the whole. The supplementary materials have a variety of names, including 'participation' and 'precaution'; and their practical content is still being developed.

Now the hazards we face are more diffuse, and in their own way more threatening. There are concerned publics, capable of acting in a co-ordinated way and directly affecting government policies for the environment and whole industries. We may say that in such issues, facts are uncertain, values in dispute, stakes high and decisions urgent. The traditional peer communities, formerly restricted to qualified experts, are now extended to include citizen participants at many levels.

The management of these new processes presents many difficulties. It is to the credit of Dr. Stirling and his colleagues that the problems are analysed to such depth, and that such important and useful practical lessons are drawn. This report can become a valuable contribution to the resolution of an urgent problem.

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EXECUTIVE SUMMARY

An integrated overview of the four studies contained in Volume II this report is provided in Volume I, together with an executive summary and twenty six policy recommendations. Taken together, the key findings are as follows.

Debate over the relative merits of 'scientific' and 'precautionary' approaches to the management of technological risk can all-too-easily fall into a 'dichotomy trap', in which productive and creative 'solution-oriented' thinking is hampered by unnecessarily rigid contrasts - with all their associated conflicts. It is true that neither an 'anything goes' (totally permissive) approach, nor a 'stop everything' (totally restrictive) approach to the regulation of technology offers a valid, feasible or desirable way forward. Fortunately, however, neither the 'narrow risk-based' nor the 'precautionary' approaches map satisfactorily onto this artificial and sterile dichotomy. To varying extents, existing regulation includes a range of effective checks and balances. It does not necessarily provide for the approval of any technology which may be developed. Likewise, even the most progressive statutory formulations of a Precautionary Principle are circumscribed in their scope and admit a series of incremental instruments. Adoption of a precautionary approach therefore does not mean that no new technological innovation can ever be deployed. Both 'precautionary' and 'scientific' approaches can be caricatured by stigmatising them in this polarised way. Likewise, both forms of rhetoric are equally vulnerable to manipulation (or even capture) by various parties in order to achieve political or commercial objectives.

Rather than seeing 'precaution' as being in tension with 'science based regulation', research conducted under this project suggests that key elements of a precautionary approach are entirely consistent with sound scientific practice in responding to intractable problems in risk assessment such as 'ignorance' ("we don't know what we don't know") and 'incommensurability' ("we have to compare apples and pears"). These intractable problems are well-founded in the fundamental theoretical framework of the sciences underlying risk assessment. With the different assumptions adopted in different risk assessment studies often yielding results that vary by several orders of magnitude, the practical policy implications are equally profound. The acknowledgement of such difficulties under a precautionary approach may thus be seen as a more scientifically rigorous way of carrying forward the regulation of technological risk than would be their denial under a purely 'risk-based' approach. Recognising the unproductive nature of the science / precaution dichotomy, then, attention can turn to the details of the measured and incremental application of an approach which is both 'scientific' and 'precautionary' in nature. Here, the Report draws a series of detailed conclusions which fall broadly into three groups.

First, "science should be on tap, not on top". There can be no simple analytical, instrumental or institutional 'fixes' for the complexities encountered in the management of technological risks. Policy making must obviously be based on the available scientific information, but science on its own is not enough. It is documented in this project how scientific risk analysis is unavoidably and inextricably intertwined with subjective framing assumptions, values, trade-offs and expectations of surprise. The appraisal of technological risks should therefore be conducted in an open and pluralistic fashion, allowing for critical discourse as an essential part not only of the regulatory process, but of the appraisal of the technological options themselves. Only in this way can the framing assumptions adopted in risk assessment and the treatment of associated uncertainties and trade-offs be tested and validated against the wider socio-political realities. Here, the developing practice of constructive technology assessment holds a number of useful lessons for the integrating technical and socio-economic factors in the management of risk, as do techniques for accounting for the qualitative strategic properties of different technological options, such as their flexibility, resilience and diversity.

Second, there is a need for flexibility and learning in regulation itself. The management of technological risk is necessarily an incremental and context-specific undertaking. Different technological risks will warrant greater or lesser degrees of precaution at different times and different regulatory instruments will be appropriate in different contexts. Each will hold its own implications for practice, such as conventions over the burden of proof. Attention should be given to the distinguishing of the different crucial (often qualitative) characteristics displayed by different types of risk. This project has gone some way towards mapping some of the key dimensions and the measures which are more or less applicable in different contexts. In addition to the merit of flexibility, a differentiated and incremental approach also offers a way to provide for the open-ended social learning which is an essential quality in the successful management of risk. In addition, systematic attention also needs to be given to institutional and procedural arrangements for ‘early listening’ and ‘technology watch’ .

Third (and as a matter of method rather than process), it is important that we “don’t throw the baby out with the bathwater”. There are a variety of very practical and robust (often quantitative) methods which are entirely consistent with the established procedures of risk assessment and which can be applied under a broader and more pluralistic precautionary approach, taking account of a variety of contending options and their associated benefits as well as their risks. The potential and constraints of these approaches are also examined in this project, including ‘decision’, ’value tree’, ‘multi-criteria’, ‘scenario’ and ‘sensitivity’ analysis. Likewise, a series of specific discursive techniques are also available in this regard as a qualitative complement to the established quantitative procedures of risk assessment, including consensus conferences, planning cells, citizen’s juries, focus groups and deliberative polls. There is no shortage of practical operational tools for transcending the circumscribed domain of narrow-risk-based regulation and allowing the implementation of an approach to the management of technological risk which is at the same time ‘scientific’ and ‘precautionary’.

Risk Evaluation and Risk Management for Institutional and Regulatory Policy

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[*] The risk evaluation and classification concept was developed by the 'German Advisory Council on Global Change (WBGU)' in its annual report 1998 about global environmental risks. Ortwin Renn as a member and Andreas Klinke as an associate researcher have been the main conrtibutors to the risk concept. See WBGU (1999). Similar views have been published in Klinke and Renn (1999 and 2001).

1. RISK EVALUATION AND RISK CLASSIFICATION

1.1 Introduction

Risk is based on the contrast between reality and possibility (Markowitz, 1990). Only when the future is seen as at least partially influenced by human beings, it is possible to prevent potential hazards or to mitigate their consequences (Ewald, 1993). The prediction of possible hazards depends on the causal relation between the responsible party and the consequences. Because the consequences are unwelcome, risk always comprises a normative concept. The society should avoid, reduce or at least control risks. Increasing potentials of technical hazards and the cultural integration of external hazards into risk calculations increase the demand for risk science and risk management (Beck, 1986).

Thus, risks can be described as possible effects of actions, which are assessed as unwelcome by the vast majority of human beings. Risk concepts from various disciplines differ in the manner how these effects of action are grasped and evaluated. Four central questions become the focus of our attention (Renn, 1992 and 1997):

1. What are welcome and what are unwelcome effects? How do we define categories of damage and which criteria distinguish between positive (welcome) and negative (unwelcome) consequences of actions and events?
2. How can we predict these effects or how can we assess them in an intersubjective valid manner? Which methodical tools do we have to manage uncertainty and to assess probability and damage?
3. Are we able to arrange risks according to risk classes? Which characteristics are relevant to evaluate risks beside the probability of occurrence and the extent of damage? Are there typical risk categories that allow us to classify risks by priorities?
4. Which combination and which allocation of welcome and unwelcome effects do legitimate the rejection or the agreement of risky actions? Which criteria do allow us an evaluation of risks?

In order to answer these questions and to be able to carry out systematically such risk evaluations, we propose a risk classification that summarises specific risk types and determines particular strategies for a rational management of the respective risk class.

1.2 Main characteristics of risk evaluation

The central categories of risk evaluation are the *extent of damage* and the *probability of occurrence* (for the definitions see: Knight, 1921; National Research Council, 1983; Fischhoff et al., 1984; Fritzsche, 1986; Short, 1984; Bechmann, 1990; IEC, 1993; Kolluru and Brooks, 1995; Banse, 1996; Rosa, 1997). *Damage* should generally understood as negative evaluated consequences of human activities (e.g. accidents by driving, cancer by smoking, fractured legs by skiing) or events (e.g. volcanic eruptions, earthquakes, explosions).

Different to the measurement of damages, there does not exist an obvious method to validate the *probability of occurrence* (Tittes, 1986; Hauptmanns et al., 1987; Kaplan and Garrik, 1993). The term *probability of occurrence* is used for such events of damage where information or even only presumptions about the relative frequency of the event have been given, but where the precise time remains uncertain. Risk statements always describe probabilities, i.e. tendencies of event sequences, which will be expected under specific conditions. The fact that an event is being expected once on average during thousand years, does not say anything about the time when the event will actually occur.

If indicators are available for determining the probability of occurrence as well as the extent of damage, the degree of reliability associated with the assessment of each component is called *certainty of assessment*. If the *certainty of assessment* is low, one needs to characterise the nature of the uncertainty in terms of statistical confidence intervals, remaining uncertainties (identifiable, but not calculable) and plain ignorance. We use the term uncertainty, if we mean the general inability to make reliable predictions of events of damages (comp. Bonß, 1996). Uncertainty is a fundamental characteristic of risk, whereas the certainty of assessment varies between extremely high and extremely low. Even if it is not possible to make objective predictions about single events of damage on the basis of risk assessment, results of the assessment are not arbitrary (Rosa, 1997). When we have two options of action where the same unwelcome event will occur with different probability, the conclusion for a decision under uncertainty is clear: Each rationally thinking human being would choose the option of action with the lower probability of occurrence (Renn, 1996).

1.3 Risk perception

Risk perception is not orientated at stringent criteria of methodical risk assessment. Risk perception is based on personal experiences, imparted information and intuitive heuristic that have been developed in the course of the biological and later the cultural evolution. Studies about intuitive risk perception have found out that human beings do not only associate risks with physical damages, but also with interferences of social and cultural values (comp. Fischhoff et al., 1978; Covello, 1983; Slovic, 1987; Brehmer, 1987; Gould et al., 1988; Renn, 1989; Drottz-Sjöberg, 1991; Pidgeon et al., 1992; Jungermann and Slovic, 1993; Rohrmann, 1995). Technical and natural scientific risk concepts ignore these risk dimensions. Psychological and social scientific risk research has established the fundamental processes involved in risk perception, so that social and mental risk experiences could adequately be measured and explained. The risk perception research has also provided the evidence that human beings take other contextual risk characteristics as a basis in addition to probability and extent of damage for risk assessment.

The task of prediction and the establishment of rational risk policy need to incorporate risk for several reasons. At first, human beings orientate their behaviour according to their perceptions and not to scientific risk models. In some cases imagined risks can exactly generate the symptoms that will be basically generated by the respective potential of damage associated with the risk source. Psychosomatic reactions are sometimes consequences of risk perceptions (Aurand and Hazard, 1992). Second, there are further risk characteristics which do not only reflect human preferences, but should also be integrated into rational risk policy under normative aspects. Whether a damage is reversible or not, whether potential damages can affect other human beings or future generations, are all dimensions that will usually be ignored by classical risk assessments. Third, most people are not indifferent to dimensional and temporal patterns of damage allocations. Whether a risk source damages thousand people from one moment to the next or thousand people will be continuously damaged by a certain period, it is not at all the same in risk perception of the most people (Jungermann and Slovic, 1993). Normatively it is also useful to include patterns of allocation as independent assessing criteria within risk analysis because selective damages often demand more means for compensation than continuously arising damages. Additionally, human beings also associate social justice with patterns of allocation.

1.4 Rational risk evaluation

From that we consider it to be justified and necessary that both technical and natural scientific assessments and risk perceptions are integral parts of rational risk evaluations (Fiorino, 1989). The question arises how societies should decide about fundamental procedures of evaluation and management concerning uncertain consequences of collective actions. Which strategy should a society choose if the consequences of risky actions concern many people with different preferences? Philosophers and decision-making theorists have come to very different conclusions (comp. Shrader-Frechette, 1991; Leist and Schaber, 1995; Jonas, 1979 and 1990; Rawls, 1971 and 1974). We want to emphasise that scientifically based assessments about selection rules for decision options with varying degrees of uncertainty as well as precautionary approaches are both rational procedures of selection despite remaining uncertainties and ambiguities. Both procedures cannot be substituted by intuition, public opinion or political pressure. Regardless whether science-based or precautionary principle of risk evaluation or management are applied, regulatory agencies need an ethically defensible and consistent set of procedures in order to evaluate and regulate risks.

As practised in many countries, we distinguish three categories of risks for starting the rational risk evaluation process (see figure 1): the *normal area*, the *intermediate area* and the *intolerable area* (area of permission) (comp. also Piechowski, 1994). The *normal area* is characterised by

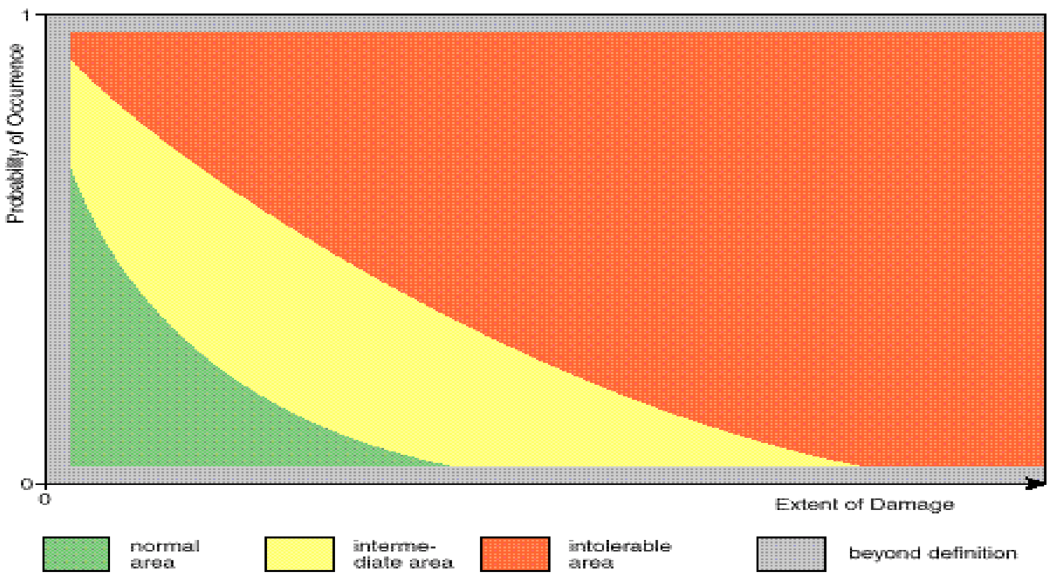
- little statistical uncertainty;
- low catastrophic potential;

- little damage when the product of probability and damage is taken;
- low scores on the criteria: persistency and ubiquity of risk consequences; and
- reversibility of risk consequences.

The normal risks are characterised by low complexity and are well understood by science and regulation. In this case the classic risk formula probability times damage is identical with the ”objective” threat. For risks located in the normal area we follow the advice of most decision-analysts who recommend risk-benefit analysis as the major tool for collective decisions based on a risk-neutral attitude.

The *intermediate area* and the *intolerable area* cause more problems because the risks touch areas that go beyond ordinary dimensions. Within these areas the certainty of assessment is contested, the statistical uncertainty is high, the catastrophic potential can reach alarming dimensions and systematic knowledge about the distribution of consequences is missing. The risks may also generate global, irreversible damages which may accumulate during a long time or mobilise or frighten the population. An unequivocal statement about the degree of validity associated with the scientific risk evaluation is hardly possible. In this case, the attitude of risk aversion is absolutely appropriate because the limits of human knowledge are reached. That’s why a simple balancing approach such as risk-benefit ratio is inadequate, since wide-ranging negative surprises are not excluded. This is the domain for precautionary strategies of risk evaluation and control, including new models of liability, new strategies of containment and risk avoidance.

Figure 1
Risk areas: normal, intermediate and intolerable area
Source: WBGU, German Advisory Council on Global Change (1999)



1.5 Additional criteria of risk evaluation

We consider it useful to include further criteria of evaluation into the characterisation of risks (Kates and Kasperson, 1983; California Environmental Protection Agency, 1994). These criteria can be derived from research studies about risk perception. They are already used or proposed as criteria in several countries such as Denmark, Netherlands and Switzerland (comp. Petringa, 1997; Löfstedt, 1997; Hattis and Minkowitz, 1997; Beroggi et al., 1997; Hauptmanns, 1997; Poumadère and Mays, 1997; Piechowski, 1994). The following criteria are relevant:

- *Ubiquity* defines the geographic dispersion of potential damages (intragenerational justice);
- *Persistency* defines the temporal extension of potential damages (intergenerational justice);
- *Reversibility* describes the possibility to restore the situation to the state before the damage occurred (possible restoration are e.g. reforestation and cleaning of water);
- *Delay effect* characterises a long time of latency between the initial event and the actual impact of damage. The time of latency could be of physical, chemical or biological nature; and
- *Potential of mobilisation* is understood as violation of individual, social or cultural interests and values generating social conflicts and psychological reactions by individuals or groups who feel inflicted by the risk consequences.

Most studies about risk perception indicate that people evaluate risks on the basis of qualitative characteristics such as personal or institutional control, voluntariness, familiarity, or an equitable allocation of risk and benefits (Jungermann and Slovic, 1993). The characteristic ”personal or institutional control" is covered by the criteria of ubiquity and persistency concerning the physical dimensions, and by the criterion of mobilisation concerning the social dimensions. From a collective point of view, voluntariness can hardly be taken into consideration as a criterion for evaluating societal risks because all relevant risks have repercussions on those who have not initiated these risks. The variable ”familiarity” as a single criterion is not meaningful for collective norms, because it is possible that people get used to unacceptable risks (e.g. accidents by driving) and are shy of new risks regardless of risk magnitude. Criteria of distribution and justice are more difficult to cover because society lacks intersubjective standards for discerning just from unjust distributions.

The question of identity between beneficiaries of hazardous activities and those people affected by risk deserves special attention. If there is identity, individual risk regulation through market mechanism is sufficient. Demanded here are only transparency for the individual risk bearer and some form of insurance to prevent society from taking the expenses for individual damage. If collective goods are at risk or major external effects are to be expected, collective mechanisms of regulation must be implemented. This can range from strict forms of liability to new forms of public involvement in risk decision-making and regulation. A case to case approach is necessary in order to deal with violations of distributive justice.

In summary our criteria and their ranges are:

- *Probability of occurrence (p)*: from 0 until 1
- *Extent of damage (d)*: from 0 to infinite
- *Certainty of assessment*:

    Confidence interval of p: high until low uncertainty boundary around the probability of occurrence

    Confidence interval of d: high until low uncertainty boundary around the extent of damage

- *Ubiquity*: local until global dispersion
- *Persistency*: low until high rate of potential restoration
- *Reversibility*: Restoration rate of damage
- *Delay effect*: a score from low to high latency between the initial event and the occurrence of the damage
- *Potential of mobilisation*: zero political relevance to high political relevance

1.6 Risk classification

Theoretically a huge number of risk types can be deduced from the eight criteria. Such a huge number of cases would not be useful for the purpose of developing a comprehensive risk classification. In reality some criteria are tightly coupled and other combinations are theoretically possible, but there are none or only few empirical examples. Considering the task of setting risk regulation priorities, risks with several extreme qualities need special attention. We have chosen a classification where similar risk candidates are classified into risk classes in which they reach or exceed one or more of the possible extreme qualities with respect to the eight criteria (see figure 2). This classification leads to six risk classes that were given names from the Greek mythology.

Events of damages with a probability of almost one were excluded from our classification. High potentials of damages with a probability of nearby one are clearly located in the ”red” area and therefore unacceptable. Such risks are rare with respect to technological hazards, but frequent with respect to natural hazards. By the same token, probability heading towards zero is harmless as long as the associated potential of damage is irrelevant. It is a characteristic of technological risk that the extent of damage is negatively correlated to the level of probability. The higher the damage the lower the probability.

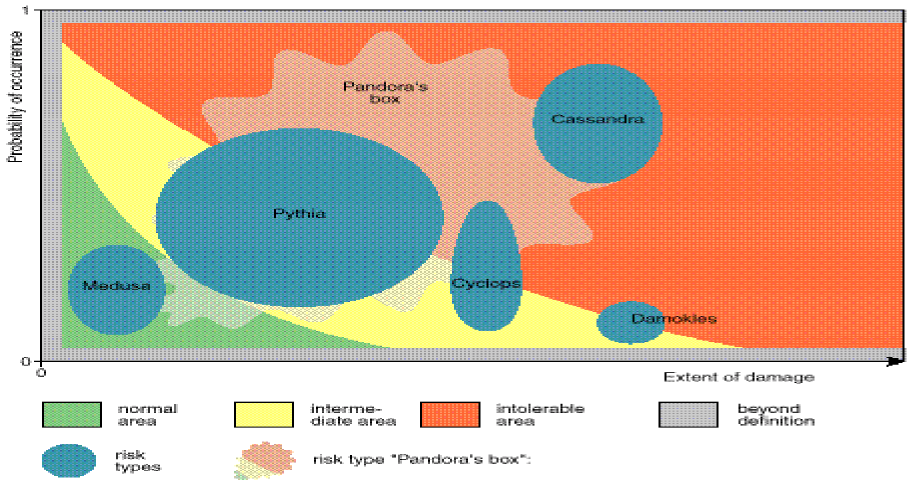
- *Risk class 'Sword of Damocles'*

  According to the Greek mythology Damocles was invited to a banquet by his king. At the table he had to sit under a sharp sword hanging on a wafer-thin thread. Chance and risk are tightly linked up for Damocles and the Sword of Damocles became a symbol for a threatening danger in luck. The myth does not tell about a snapping of the thread with its fatal consequences. The threat rather comes from the possibility that a fatal event could occur for Damocles every time even if the probability is low. Accordingly, this risk class relates to risk sources that have very high potentials of damages and at the same time very low probability of occurrence. Many technological risks as nuclear energy, large-scale chemical facilities and dams belong to this category.

- *Risk class 'Cyclops'*

  The Ancient Greek knew enormous strong giants who were punished despite their strength by only having a single eye. They were called Cyclops. With only one eye only one side of reality and no dimensional perspective can be perceived. Applied to risks it is only possible to ascertain either the probability of occurrence or the extent of damage while the other side remains uncertain. In the risk class *Cyclops* the probability of occurrence is largely uncertain whereas the maximum damage can be estimated. Some natural events like floods, earthquakes and volcanic eruptions, but also the appearance of AIDS belong to this category.

<u>Figure 2</u>
<u>Risk classes</u>
<u>Source: WBGU, German Advisory Council on Global Change (1999)</u>



- *Risk class 'Pythia'*

  The Greeks of the antiquity asked their oracles in cases of uncertainty. The most known is the oracle of Delphi with the blind prophetess Pythia. Pythia's prophecies were always ambiguous. It certainly became clear that a great danger could threaten, but the probability of occurrence, the extent of damage, the allocation and the way of the damage remained uncertain. Human interventions in ecosystems, technical innovations in biotechnology and the greenhouse effect belong to this risk class where the extent of changes is still not predictable.

- *Risk class 'Pandora's box'*

  The old Greeks explained many evils and complaints with the myth of Pandora's box – a box which was sent to the beautiful Pandora by the king of the gods Zeus. It only contained many evils and complaints. As long as the evils and complaints stayed in the box, no damage at all had to be feared. However, when the box was opened, all evils and complaints were released which than irreversibly, persistently and ubiquitously struck the earth. This risk class is characterised by both uncertainty in the criteria probability of occurrence and extent of damage (only presumptions) and high persistency. Here, persistent organic pollutants and endocrine disruptors can be quoted as examples.

- *Risk class 'Cassandra'*

  Cassandra was a prophetess of the Trojans who certainly predicted correctly the victory of the Greeks, but her compatriots did not take her seriously. The risk class Cassandra describes a paradox: the probability of occurrence as well as the extent of damage are known but it hardly emerges dismay in the present because the damages will occur after a long time. Of course risks of the type Cassandra are only interesting if the potential of damage and the probability of occurrence are relatively high. That's why this type is located in the intolerable "red" area. A high degree of the delay effect is typical for this risk class, i.e. a long period between the initial event and the impact of the damage. An example of this effect is the anthropogenic climate change.

- *Risk class 'Medusa'*

  The ancient mythology tells that Medusa was one of three snake-haired sisters of the Gorgons whose appearance turns the beholder to stone. Similar to the Gorgons who spread fear and horror as an imaginary mythical figure some new phenomena have an effect on modern people. Some innovations are rejected although they are hardly assessed scientifically as threat. Such phenomena have a high potential of mobilisation in public. Medusa was the only sister who was mortal – if we transfer the picture to risk policy – Medusa can be combated by effective argumentation, further research and communication in public. According to the best knowledge of risk experts risks of this type are located in the normal area. Because of specific characteristics these risk sources frighten people and lead to heavy refusal of acceptance. Often a large number of people are affected by these risks but harmful consequences cannot statistically be proven. A typical example are electromagnetic fields.

Table 1: Overview of the risk classes, main characteristics and examples
Source: WBGU, German Advisory Council on Global Change (1999)

Sword of Damocles	*p* low (towards 0); *d* high (towards infinite); *confidence intervals of p* and *d* low	• nuclear energy • large-scale chemical facilities • dams • meteorite impacts
Cyclops	*p* uncertain; *d* high; *confidence interval of p* high; *confidence interval of d* rather low	• floods • earthquakes • volcanic eruptions • AIDS infection • mass developments of anthropogenically influenced species • triggering of nuclear, biological and chemical weapons systems • collapse of thermohaline circulation
Pythia	*p* uncertain; *d* uncertain (potentially high); *confidence intervals of p and d* high;	• increasing greenhouse effect • release and spread of transgenic plants • BSE • certain genetic engineering applications • instability of the West Antarctic ice sheets
Pandora's box	*p* uncertain; *d* uncertain (only presumptions); *confidence intervals of p and d* uncertain (unclear); *persistency* high (several generations)	• persistent organic pollutants (POPs) • endocrine disruptors
Cassandra	*p* high; *d* high; *confidence interval of p* rather high; *confidence interval of d* rather low; *delay effect* high	• anthropogenic climate change • destabilisation of terrestrial ecosystems
Medusa	*p* rather low; *d* rather low (exposition high); *confidence interval of p* rather high; *confidence interval of d* rather low; *potential of mobilisation* high	• electromagnetic fields

As we have seen each risk class indicates a respective character concerning the degree of incertitude. We apply this term to describe the level of knowledge, uncertainty or ignorance concerning the main criteria probability of occurrence and extent of damage. The reliability of the certainty of assessment depends on this degree of incertitude. The following table provides an overview:

Table 2: Degree of incertitude concerning probability of occurrence and extent of damage

Degree of incertitude	Main criteria	Risk class
Knowledge and certainty	Probability of occurrence and extent of damage are *known*	• Sword of Damocles • Cassandra • Medusa
Uncertainty	Probability of occurrence or extent of damage or both are *uncertain*	• Cyclops • Pythia
Ignorance	Probability of occurrence and extent of damage are *highly unknown*	• Pandora's box

2. RISK MANAGEMENT AND POLITICAL REGULATIONS

The main objective of the risk classification is to gain an effective and feasible policy tool for the evaluation and the management of risks. The characterisation provides a knowledge base for designing specific political strategies and measures tailored for each risk class. The strategies pursue the goal of transforming unacceptable into acceptable risks, i.e. the risks should not be reduced to zero but moved into the "green" area, in which routine risk management becomes sufficient to ensure safety and integrity. All strategies and respective measures are arranged according to priorities. In almost all cases more than one strategy and more than one measure are naturally appropriate and necessary. If resources are limited, strategies and measures should be taken in line with the priority list. The following part lists the prior strategies and the prior measures recommended for each risk class.

2.1 Science-based strategies and instruments for the risk class *Sword of Damocles*

For risks from the category *Sword of Damocles* three central strategies are recommended. The prior strategy implies science-based regulations because the probability of occurrence as well as the extent of damage are relatively well-known. As a result the science-based assessment of certainty is adequate. Therefore, the negative effects of the risk potential need to be addressed. First, the potential of disasters must be reduced by research to develop substitutes and technical changes. The second strategy is a combination of science-based measures and precautionary regulations. Within in the second strategy resilience must be increased, i.e. the power of resistance against surprises. The third priority is obviously based on the precautionary principle of remediation: The emphasis here is on effective emergency management. The same applies for the other risk classes with the exception of the risk class *Medusa*.

Within the scope of the first strategy to reduce the damage potential, we recommend more research for developing substitutes and technical measures for the reduction of disaster potential as well as the realisation of measures to reduce the extent of damage. For example, in the past the primary strategy of nuclear energy was to reduce the probability of a core melt-down. In order to move this risk from the intermediate area to the normal area, this strategy was insufficient. More useful would have been a change towards reducing the catastrophic potential (meanwhile this seems to take place). Imposing strict liability rules might provide an additional incentive for reducing the catastrophic potential: operators are then encouraged to improve their knowledge and to reduce the remaining risks. At the same time, it is necessary to develop alternatives with a lower catastrophic potential in order to replace technologies that belong to the *Damocles* category. For establishing and testing these alternatives, subsidies are necessary.

Within the scope of the second strategy it is necessary to increase the resilience against the risk potentials. Therefore capacity building is required so that institutional and organisational structures can be improved and strengthened in order to have control over licensing, monitoring, training etc. Additionally, technical procedures to increase the resilience must be established or, if they already exist, be improved. Such procedures include technical redundancy, organisational security units, integration of latitudes, buffers and elasticities and diversification, i.e. the local dispersion of risk sources. Resilient organisation models and effective licensing procedures should be demanded when hazardous technology is transferred to other countries. International control and monitoring should also be strengthened and an international safety standards authority should be established.

Table 3: Science-based strategies and instruments for the risk class *Sword of Damocles*
Source: WBGU, German Advisory Council on Global Change (1999)

Strategies			Instruments
a)	Reducing damage potential	-	Research to develop substitutes and to reduce the potential of disasters
		-	Technical measures for reducing the disaster potential
		-	Stringent rules of liability
		-	International safety standards authority
		-	Subsidies of alternatives for the same use
		-	Containment (reducing the damage extension)
		-	International coordination (e.g. averting the hazard of meteorites)
b)	Increasing resilience	-	Capacity building (permit, monitoring, training)
		-	Technical procedures of resilience (redundancy, diversification etc.)
		-	Blueprint for resilient organisations
		-	Procedures of permit as model
		-	International control (IAEO)
		-	International liability commitment
c)	Emergency management	-	Capacity building (protection from emergencies)
		-	Training, education, empowerment
		-	Technical protection measures, including strategies of containment
		-	International emergency groups (e.g. fire brigade, radiation protection)

The third priority refers to emergency management. This strategy is not regarded as insignificant, however, a strategy of damage limitation should stay behind the primary rationale of reducing risk strategies. In this domain, capacity building must be increased by developing and promoting national programs of emergency protection. Successful measures of emergency protection and techniques in forms of training, education and empowerment can be transferred to local risk manager.

In addition, technical measures of protection and measures to reduce the extent of damage have to be enforced. Finally, an international preventing disaster relief, like the "International Decade for Natural Disaster Reduction (IDNDR)" initiated by the UN, is helpful for anthropogenically caused disasters.

2.2 Science-based (and precautionary) strategies and instruments for the risk class *Cyclops*

In the case of the risk class *Cyclops*, the uncertainty concerning the probability of occurrence is the starting point for regulative measures. Because the possible extent of damage in the case of a catastrophe is relatively well known, both science-based strategies and strategies based on the precautionary principle are required. First of all we recommend increased research and intensive monitoring for a better assessment of the probability distribution. Until such results are available, strategies to prevent unwelcome surprises are useful (including strict liabilities). Preventing measures for disasters are important on international level because the damage potentials within affected countries with high vulnerability can reach precarious extensions.

First priority is assigned to scientific research concerning the probability of occurrence. Additionally, international monitoring by national and international risk centres should supplement all local efforts. That could be fulfilled by the establishment of an "UN Risk Assessment Panel" that has the function to set up a network among the national risk centres and to gather and assess knowledge about global risks. Something similar could and should be organised on the European level.

Within the scope of the second strategy unwelcome surprises have to be prevented. This could happen by improving strict liabilities or by compulsory insurance if certain conditions are met. The appropriate instruments of capacity building and technical measures correspond to the instruments listed under the risk class *Sword of Damocles*.

Table 4: Science-based (and precautionary) strategies and instruments for the risk class *Cyclops*
Source: WBGU, German Advisory Council on Global Change (1999)

Strategies		Instruments
a)	Ascertaining the probability of occurrence	- Research to ascertain numerical probability - International monitoring by: • National risk centres • Institutional network • Global risk board - Technical measures for calculating the probability of occurrence
b)	Prevention against surprises	- Strict liabilities - Compulsory insurance for those generating the risks (e.g. floods, housing estates) - Capacity building (permit, monitoring, training) - Technical measures - International monitoring
c)	Emergency management or reducing the extent of damage	- Capacity building (protection from emergencies) - Training, education, empowerment - Technical protection measures, including strategies of containment - International emergency groups (e.g. fire brigade, radiation protection)

Within the third strategy, emergency management would include the same measures that have been postulated for the risk class *Sword of Damocles*.

2.3 Precautionary strategies and instruments for the risk class *Pythia*

Within the risk class *Pythia* the criteria probability of occurrence as well as the extent of damage have a high quality of uncertainty. The result is that science-based assessments are either highly contested or genuinely absent. Therefore, the prior risk management strategy must be precaution. This includes a strict implementation of instruments and regulations based on the precautionary principle. The second strategy is directed towards improving the knowledge base. More basic research is required. At the same time, strategies of prevention in particular limiting the use of the risk source in specific areas or spaces, should be encouraged because the extent of damage could reach global dimensions. Geographical and temporal measures of containment are indispensable.

With respect to the instruments, precaution has top priority. We recommend institutional regulations such as ALARA (as low as reasonably achievable), BACT (best available control technology), technical standards etc. and other limitations. International conventions for controlling, monitoring and safeguarding are also necessary. The instruments to reduce the extent of damage and capacity building are the same as for the risk classes mentioned above.

Table 5: Precautionary strategies and instruments for the risk class *Pythia*
Source: WBGU, German Advisory Council on Global Change (1999)

Strategies			Instruments
a)	Strict implementation of the precautionary principle	- - - -	Institutional regulations as ALARA, BACT, technical standards etc. Fund solutions International conventions for controlling, monitoring and security measures etc. Containment (reducing the extension of damage) - Capacity building (permit, monitoring, training) - Technical procedures of resilience (redundancy, diversification etc.)
b)	Improving knowledge	- -	Research to ascertain the probability of occurrence and the extent of damage International early warning system by: • National risk centres • Institutional network • Global risk board
c)	Emergency management	- - - - -	Containment strategies Capacity building (protection from emergencies) Training, education, empowerment Technical protection measures International emergency groups (e.g. for decontamination)

The improvement of knowledge has second priority so that future risk analysis can provide a higher level of validity and certainty. Research on how to ascertain the probability of occurrence and the extent of damage is needed. Additionally, an international early warning system is necessary as for the risk class *Cyclops*.

The third strategy of emergency management comes close to measures of the previous risk classes.

2.4 Precautionary strategies and instruments for the risk class *Pandora's box*

The risks of *Pandora's box* are characterised by uncertainty concerning the probability of occurrence and the extent of damage (only presumptions). The major problem here, however, is ubiquity and persistency. As a result, the science-based assessment of certainty is also weak. To manage such a high uncertainty, strategies based on the precautionary principle are again necessary. Research efforts to develop substitutes and regulatory measures to contain or to reduce the risk sources are absolutely essential because the negative consequences of the risk sources are unknown. In the most unfavourable case, however, the consequences can reach global dimensions with irreversible effects. Containment strategies need to be implemented on the international level.

The development of substitutes has priority over all other strategies. Concerning the research and development of substitutes the measures correspond to those that we included in the list for the risk class *Sword of Damocles*. In addition, this risk type requires wide-ranging research efforts that need adequate financial support.

In a second step the risk potentials should be decreased by reducing dispersion or exposure of chemicals or by prohibiting them completely. Regulatory procedures should limit quantities through environmental standards or even more advisable by means of certificates. In some cases the use of strict liability is appropriate. Furthermore instruments of technical safety measures and capacity building complement the regulatory requirements.

The third strategy of emergency management corresponds to the other risk types. An international emergency group combating unwelcome surprises should be installed. The international emergency group for nuclear decontamination of the IAEO can serve as an example.

Table 6: Precautionary strategies and instruments for the risk class *Pandora's box*
Source: WBGU, German Advisory Council on Global Change (1999)

Strategies		Instruments	
a)	Developing substitutes	-	Research to develop substitutes
		-	Supporting basic research
		-	Incentives to use less harmful substitutes
		-	Subsidies for developing alternative production systems
b)	Reduction and containment	-	Regulatory policy for limitation of exposures through environmental standards etc.
		-	Use of incentive systems (certificates)
		-	Strict liability, if useful
		-	Improving and developing technical procedures of support
		-	Capacity building (technical know-how, technology transfer, education, training)
		-	Joint implementation
c)	Emergency management	-	Capacity building (protection from emergencies)
		-	Technical protection measures, including containment strategies
		-	Training, education, empowerment

2.5 Consciousness building strategies and instruments for the risk class *Cassandra*

The risks of the risk class *Cassandra* are not associated with scientific uncertainty, but people take the risks not seriously because of the lingering delay between the initial event and the damage. The probability of occurrence as well as the extent of damage are relatively known, i.e. the science-based assessment of certainty is relatively good. Due to the tendency of democratic governments to rely on short time legitimisation periods (short election periods), politics often lack the motivation to take care of long-term hazards. Therefore, strategies are needed to build up consciousness and to initiate common efforts of institutions for taking responsibility. Measures of collective commitment (e.g. code of conduct for multinational enterprises) and long-term international institutions (UN or European Risk Assessment Panel) should be conducive to strengthen the long-term responsibility of the international community. Limitations of quantities are also appropriate to reduce these risks. Although the strategies are mainly oriented toward building consciousness, relevant precautionary instruments and measures as, for example, limitations, fund solutions and capacity building are additional in elements of a regulatory regime for this risk type.

Table 7: Consciousness building strategies and instruments for the risk class *Cassandra*
Source: WBGU, German Advisory Council on Global Change (1999)

Strategies		Instruments
a)	Strengthening the long-term responsibility of key actors	- Self-commitment, code of conduct of global actors - Enhancing of participation, empowerment and institutional security as a means to foster long-term responsibility - Measures against governmental break down - Fund solutions - International coordination
b)	Continuous reduction of risk by introducing substitutes and setting limitations of exposure	- Use of incentive systems (certificates and fees) - Strict liability, if useful - Regulatory limitations of quantities by environmental standards (also international standards) - Improving and developing technical procedures of support - Capacity building (technical know-how, technology transfer, education, training) - Joint implementation
c)	Contingency management	- Capacity building (recultivation, protection from emergencies) - Technical protection measures, including containment strategies - Training, education, empowerment

If there is a relevant delay between the initial event and the consequences, the first strategy should be to strengthen long-term responsibility and to plan for future generations. The goal is the self-commitment of the states and relevant actors (e.g. multinational enterprises). It is possible that funds could be an effective instrument to mitigate at least the consequences that are likely to occur in the future. On the individual level, potentially affected people can become more conscientious and aware of the problems if they are involved in risk regulations through participation and empowerment.

The second strategy implies the continual reduction of risk potentials, for example the need of developing substitutes. Risk potentials which cannot be substituted should at least be reduced through limitations of quantities or by limiting the field of application (containment strategies). The necessary instruments have already been covered above. The instruments of the third strategy of emergency management correspond to the other risk classes, too.

2.6 Confidence-building strategies and instruments for the risk class *Medusa*

The probability of occurrence and the extent of damage of the risk class *Medusa* are rather known, i.e. the science-based assessment of certainty is at least satisfactory. The hazardous nature of the risks is mainly based on the subjective perception that can lead to stress, anxiety and psychosomatic malfunctions. The required strategies focus on building confidence and trustworthiness in regulatory bodies. Together with confidence-building, science-based improvements of knowledge as a means to reduce the remaining uncertainties are necessary. Clarification of facts, however, is not enough, and will not convince people that the risks belong in the ”green” area. What is needed is the involvement of affected people so that they are able to integrate the remaining uncertainties and ambiguities into their decision-making.

Table 8: Confidence-building strategies and instruments for the risk class *Medusa*
Source: WBGU, German Advisory Council on Global Change (1999)

Strategies			Instruments
a)	Confidence-building	-	Establishment of independent institutions for information and clarification
		-	Increasing the chances of participation with the commitment to set up priorities
		-	Support of social science concerning the potential of mobilisation
		-	Procedures of permit with participation of affected people as model
		-	International control (IAEO)
		-	International liability commitment
b)	Improving knowledge	-	Research to improve the certainty of assessment
		-	Governmental support of research (basic research)
c)	Risk communication	-	Two-way communication
		-	Involvement of citizens
		-	Informed consent

The extent of damage and the probability of occurrence of this risk type are not dramatic, the potential of mobilisation is high, however. In order to inform the public about the real extent of damage and the probability of occurrence, confidence-building measures are necessary. Independent institutions with high social esteem are important brokers for informing the public about the results of scientific research. Information is not enough, however. The affected people should be given the opportunity to participate in decision-making and licensing procedures. Social scientific research is essential to find out about the motives of people and to provide platforms for conflict resolution.

In addition, the knowledge base about the risk potential needs to be improved. Risks with high mobilisation potential are often characterised by high exposure (ubiquity). Precaution is hence necessary, but if science-based data confirm the innocuousness of the respective risk sources, risk reduction measures are not necessary. Research activities produce more certainty and unambiguity is still needed, however, in order to be on the safe side.

3. CONCLUSION: RISK EVALUATION AND RISK CLASSIFICATION IN A DELIBERATIVE PROCESS

3.1 Synopsis: science-based, precautionary and discursive strategies

A comparative view on the risk classification scheme indicates that there are mainly two risk classes that require predominantly science-based strategies, two risk classes that require the application of the precautionary principle and two classes that place priority on discursive strategies and measures aimed at building confidence and consciousness. That does not mean that within each risk class the other strategies and instruments have no place, but they take a "back seat".

Table 9: Risk classes and their primary strategies

Primary strategy Risk class	Science-based	Precautionary	Discursive
Damocles	• Reducing disaster potential by developing substitutes	• Increasing resilience by capacity building	
Cyclops	• Ascertaining the probability of occurrence	• Prevention against surprises through liabilities and compulsory insurance	
Pythia		• Strict implementation of the precautionary principle as ALARA, BACT, technical standards	
Pandora's box		• Developing substitutes and supporting basic research	
Cassandra			• Strengthening the long-term responsibility by self-commitment, code of conduct
Medusa			• Building confidence by establishing independent institutions for information and clarification

At first we want to focus on risk potentials which can adequately managed by science-based strategies and regulations. Within the risk class *Damocles* (examples are nuclear energy, large-scale chemical facilities or dams) the most important risk criteria probability of occurrence and extent of damage are relatively well-known so that there is little uncertainty left. Based on this knowledge science-based strategies and instruments for risk management are most appropriate. Within the risk class *Cyclops* a mixture of science-based and precautionary strategies are useful because the risk potentials are characterised by good knowledge on the extent of damages, but the probability of occurrence is relatively uncertain. Typical representatives of this risk category are mass developments of anthropogenically influenced species or risk potentials of nuclear, biological and chemical weapons.

The risk classes *Pythia* and *Pandora's box* require strategies and instruments based on the precautionary principle. Typical representatives of these risk classes are the release and spread of transgenic plants and certain genetic engineering applications, the increasing greenhouse effect, persistent organic pollutants and endocrine disruptors. These risk potentials are characterised by a relatively high degree of uncertainty concerning the two main criteria probability of occurrence and extent of damage. As a result, much uncertainty prevails. To cope with these uncertain risk potentials and to reduce uncertainty, the selected risk management and policy regulations are derived from the application of the precautionary principle.

The third strategy of discourse is essential if either the potential of a wide-ranging damage is ignored (due to the delay effect) or – the opposite – harmless effects are perceived as major threats. Discursive procedures include environmental education, strengthening awareness and mutual learning. In addition, discursive methods of planning and conflict resolution are required. Within the risk classes *Cassandra* and *Medusa* these discursive strategies and instruments have priority.

Discursive procedures can also be useful within the other risk classes. If expert opinions and scientific expertise are ambiguous or even controversial, an expert discourse is necessary, where arguments are exchanged and a consensual agreement about the reasons for dissenting views can be accomplished. If (affected) people are strongly mobilised by risk potentials, public discourses are required where experts, politicians and citizens contribute to the political decision-making processes.

3.2 Risk dynamic

The ultimate goal of all measures taken for reduction is to move risks from the intermediate area to the normal area. In stating this aim, we share the general understanding that it cannot be the aim of any risk policy to reduce all risks down to zero, but rather to move high risks into the ”green” area, e.g. they reach a scale at which the common methods of risk-benefit assessment can be applied by market participants and by state regulators. The management of transboundary or global risks located in the normal area do not necessarily require international efforts. Assistance in establishing effectively operating regulatory authorities, functioning insurance markets and effective contingency measures are sufficient. If a transboundary or global risk is identified as belonging to one of the risk classes localised in the intermediate area, then international measures are indeed called for in order to move the risk from the intermediate ”yellow” area to the normal ”green” area.

This movement will follow a process passing through several stages. Regardless of the success of individual measures, a risk can move from one class to another without directly entering the ”green” area. Figure 3 illustrates typical movements from class to class.

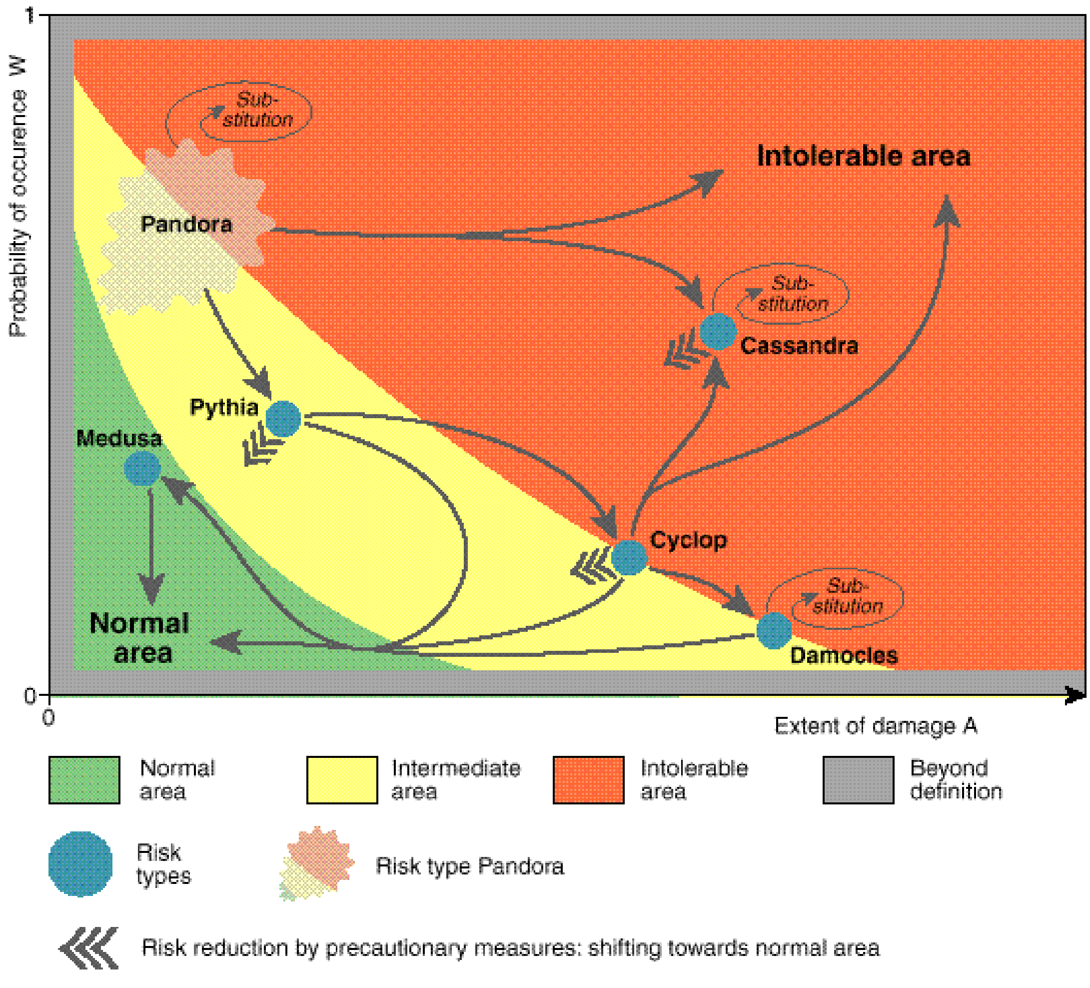
In general, we may distinguish between two types of measure: measures aimed at improving knowledge (through research and liability), and regulatory measures impinging upon critical, class-specific quantities (probability, extent of damage, irreversibility, persistence, delay effect and mobilisation). As Figure 3 indicates, improved knowledge generally leads to a movement from one class of risk to another, for instance, from *Pandora* to *Pythia*, from *Pythia* to *Cyclops* and from there to *Damocles* or *Medusa*, i.e. the regulating framework moves from precautionary strategies to more science-based strategies. Measures acting upon a specific critical quantity can similarly trigger a cascade movement or can cause a direct move into the normal area.

The following section explains this movement from one class of risk to another using a fictitious example. Imagine a substance that is used internationally, is highly persistent and for which there are reasonable grounds to assume that it causes irreversible effects. This risk belongs in the Pandora class. It is located in the upper third of the intermediate area, since the confidence intervals of the uncertainty bounds extend into the unacceptable area. A risk of this class suggests two primary strategies: Expanding knowledge and limiting the risk potential. Let us first examine the outcome of expanding knowledge: The knowledge pertaining to the risk can be further quantified, in the process of which the assumption of irreversible consequences or of high persistence may be substantiated. If this is the case, a substitution of the substance or even a ban is urgently called for. The risk is thereby unequivocally moved into the prohibited area. If a large period of time elapsed between the triggering event (human or environmental exposure) and its consequence, the prospect of taking direct influence through a ban or restriction would be minute. We then would move towards the *Cassandra*-type risk. To handle this risk, long-term responsibility needs to be strengthened and principal actors need to be mobilised so that effective strategies of substitution are introduced or at least containment strategies are implemented.

Let us assume in our illustrative example that the spatial distribution of this substance can indeed be limited such that ubiquitous dispersal is prevented. In this case, the risk is moved to the *Pythia* class, as the probability of occurrence and the extent of damage are still both subject to major uncertainties. The next step in this case would be to determine the extent of damage more clearly. Let us then assume that there are grounds to determine or estimate measurable damage and that this damage seems large enough to preclude locating the risk in the normal area. Under these conditions, movement continues in the direction of the Cyclops class. Cyclops forms a pivotal node in figure 3, as risks can undergo transmutation from there to a variety of other classes. If, for instance, we can succeed in determining the probability of occurrence and this is relatively low, then the risk can be categorised as belonging to the *Damocles* class, characterised by high extent of damage and low probability. If, however, probability is found to be high and there is a delay effect, the risk again moves towards the *Cassandra* category. Without this delay effect, a ban or a rapid substitution can be expected (movement to the prohibited area). If technological or other measures can be applied to reduce the extent of damage to a 'normal' level, nothing now stands in the way of movement to the normal area.

On the other hand, if the disaster potential remains very high despite reduction efforts, the risk lands in the *Damocles* class. From here, too, it can be moved to the normal area through a two-pronged strategy of improving knowledge and reducing disaster potential. If all reduction tools fail, then a fundamental decision is due as to whether the benefit associated with this risk is considered to be so substantial that the high potential for damage is tolerated since the probability of occurrence is low. If the outcome of this decision is negative, the risk moves into the prohibited area.

Figure 3
Risk dynamic
Source: WBGU, German Advisory Council on Global Change (1999)



For all types of risks, the desired movement to the normal area can proceed via the *Medusa* class. Thus, in our fictitious example, the public may have little confidence in the purported reduction of damage potential. By way of illustration, we only need to recall the uproar caused in Germany by the "Castor" nuclear waste transports. Even if the health risk from radiation is assessed as low in terms of both probability and extent of damage – which appears justified considering the isolated cases of radiation dose limits being exceeded – the loss in terms of credibility and reliability is large enough to generate a major political and psychological mobilisation effect. Acting on a long history of suffering in public risk debates and their political ramifications, many risk regulators may prefer to opt for a ban, even though both probability and extent of damage indicate a normal risk. In such a case, measures aimed at building confidence and direct participation are necessary in order to make the public aware of the 'normality' of the risk, to give the public more control over regulation activities and, at the same time, to commit technology operators to handle the risk as required by law. In addition, a need always remains to critically review whether the measures instituted have indeed led to the intended risk reduction.

After passing through all these stations, the risk will finally land in the normal area. This cascade movement presupposes intensively tackling the risks to be assessed, and continuously monitoring and scientifically informing the risk reduction measures to be taken. This requires time, institutional provisions and resources. Given the extent of transboundary or global threats, investments in transboundary and international risk management are worthwhile.

The analytical framework of risk classes put forward here and the associated dynamic conception of measures offer a logically consistent and politically practicable procedure. This concept can help national governments, the European community and the international community at large to concentrate on those risks that have the potential to emerge as serious threats, while risks in the normal area are adequately addressed by national regulatory structures. Concentrating on essentials is in fact an important message to the public, which, beset by widespread confusion as to the damage potential of risks, expects the policy-makers and the scientific community to deliver orientation and certainty in action. At the same time, the categorisation in risk classes and the implementation of class-specific measures can help society to deal with risks effectively and targetedly, and can instruct risk managers in industry and polity on how to handle risks rationally.

3.3 Who can make the decision on the classification? An analytical-deliberative approach

In the deliberative democracy many political and societal problems and their resolving remain contentious, although the actors in the political arena attempt to achieve consensus on the choice of the appropriate regulations and measures (Giddens, 1997). Why do a rational risk evaluation and an understanding risk classification have relevance for a societally acceptable risk management in the deliberative democracy? Within the deliberative process the political decision-making comprises public discussion and consultation expressing all interests, i.e. political action in a representative democracy should be characterised by transparency and communication (Giddens, 1997; comp. Schmalz-Bruns, 1995). Because in a deliberative democracy different means can lead to a consensus, it would be practical and effective that the actors in the society agree on norms and procedures to evaluate political decisions or to manage controversial questions and issues. If the results reflect the previous discourse, the legitimacy of the political decisions increase (Miller, 1993). Our risk evaluation and the deduced risk management are the attempt to initiate a deliberative process, because rationally understanding criteria of evaluation are used, externally revealed and communicated. For an adequate risk evaluation and risk management the democratic deliberative process should fulfil three main functions:

- Involving and consulting public in the political decision making process;
- transparency of the political decisions; and
- risk communication.

The task of risk management, including the selection of political strategies and measures for action directed at each risk type is mainly addressed to political regulators. The addressees are national governments, the European community and international institutions. They are obliged by law or statute to legitimise response strategies and measures and to implement them effectively. But the question arises whether political or administrative institutions have the competence and the knowledge to classify risks. Who can classify complex technological or environmental risk potentials? Should nuclear energy or gene technology be subsumed under the risk class *Damocles* or the risk class *Pythia*? Is the complex phenomenon of climate change a risk potential that should be assigned to one risk category or does climate change comprise different risk sources and potentials which should be classified accordingly?

For a rational risk evaluation, profound scientific knowledge is required, especially, with regard to the main criteria of risk evaluation – probability of occurrence, extent of damage and certainty of assessment – and to the additional criteria as well. This knowledge has to be collected by scientists and risk experts who are recognised and leading authorities in the respective risk area. The experiences of risk experts from different technological or environmental fields crystallise into a comprehensive risk knowledge. This “state of the art” enables scientists and experts to provide the data base for each of the eight evaluation criteria. If there is dissent among experts, special techniques of classification such as Delphi procedures or meta-analyses may be required to overcome superficial disagreements and to produce defensible arguments for different positions. If there is no controversy about the data base, the classification can be performed almost automatically. For practical reasons, scientific advisory bodies or specialists of risk managing agencies should take the responsibility for the classification.

For example, in the framework of the latest annual report about the management of global risks the “German Advisory Council on Global Change” suggested to substructure the phenomenon of climate change into different risk potentials and characterise these potentials on the basis of the eight risk criteria. The Council developed different risk management strategies for each risk type (WBGU, 1999). The results were compiled by leading scientists who know the relevant insights and are able to reflect the "state of the art". The results of these considerations are then communicated to the respective ministries (environment as well as science and research).

It should be emphasised that classification is not a scientific task, but builds upon the deliberative function of expert opinions for political decision making. On the national level, advising committees assembled by scientists and other experts can fulfil this deliberative function as long as they are integrated into democratic structures. On the European and international level, equivalent structures are either lacking or need to be strengthened. To classify technological and environmental risks within the European and international governance, for example, The EU-commitology structure could be amended in order to provide the necessary deliberative function and so reduce the deficit of knowledge input.

Connection between deliberative plurality and uncertainty concerning knowledge

If contentious issues prevail and the rating of risks remain controversial, scientific input is only the first step of a more complex classification procedure. It is still essential to compile the relevant data and the various arguments for the positions of the different science camps. Procedures such as using the "Pedigree Scheme" by Funtowics and Ravetz (1990) might be helpful to organise the existing knowledge. In a second step, the information, including all uncertainties and ambiguities, needs to be assessed and evaluated by a political body. We recommend discursive and deliberative methods of decision making within such bodies. In addition, if the scientific risk evaluation is questioned by the public and lead to a high degree of mobilisation, a public discourse among scientists, political decision makers and citizens is required to classify these risks. Without consulting public interest groups and those who are affected by the decision, a synthesis of expert opinion and public concern cannot be achieved. In this deliberative process it is relevant that the actors mutually learn. The report of the National Academy of Sciences stresses the need for a combination of evaluation and discourse named as 'analytical-deliberative approach' (Stern and Fineberg, 1996). Especially the risks of the risk classes *Cassandra* and *Medusa* need the linkage of risk evaluation and discourse in order to introduce learning processes for building consciousness and confidence. But also the science-based and precautionary risk types require an analytical-deliberative procedure, if questions and problems of evaluation and classification are contentious and resolving strategies of risk management generate dissent.

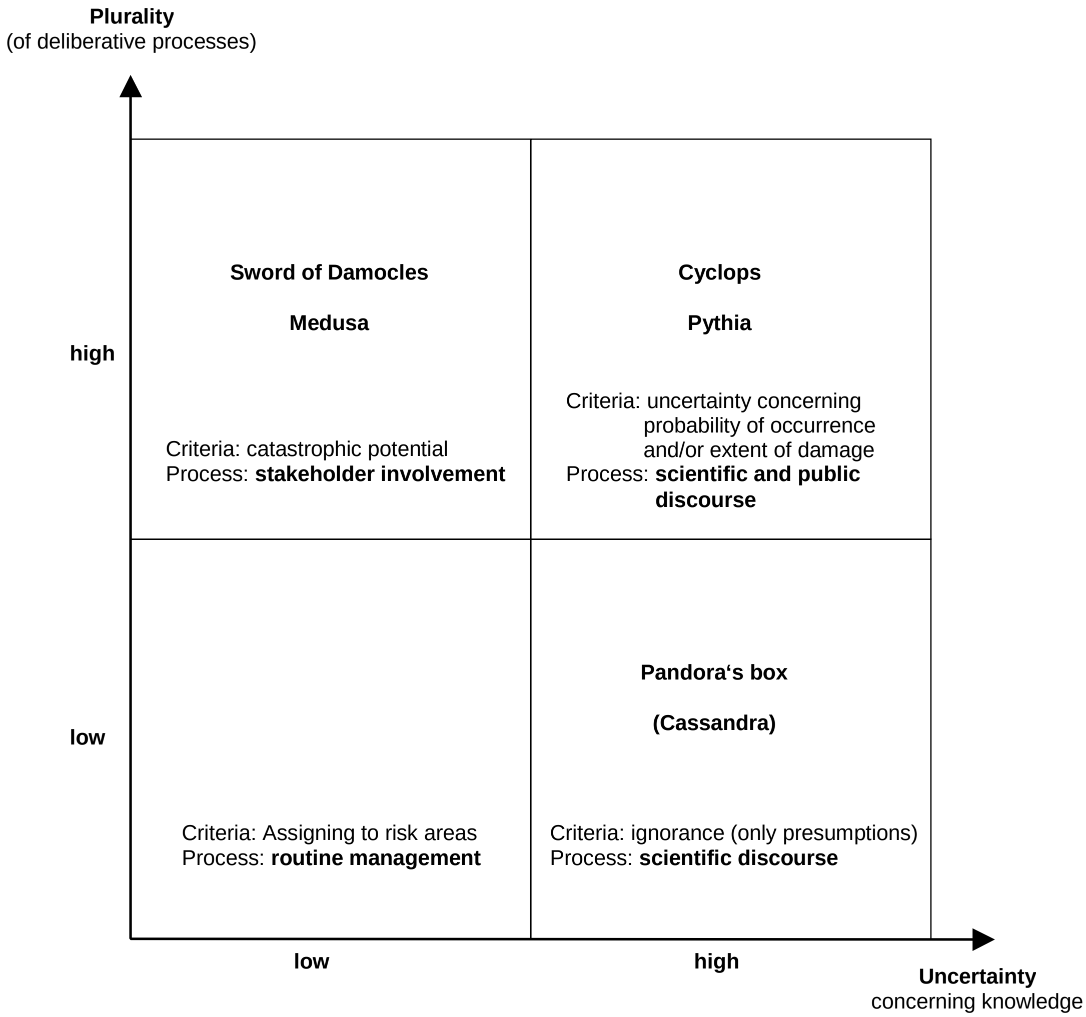
In the literature there are many different classifications of discourses (Bacow and Wheeler, 1984; Zilleßen, 1993). For example, one can argue about facts, about assessments, about demands for action or about aesthetic opinions. With the respect to the management of risks, a classification of four categories seems useful:

Within a *cognitive discourse* experts (not necessarily scientists) argue over the factual assessment with respect to the eight criteria. The objective of such a discourse is the most adequate description or explanation of a phenomenon (for example the question, which climate impacts are to be expected by the emission of specific substances). The more complex, the more multi-disciplinary and the more uncertain a phenomenon appears to be, the more necessary is a communicative exchange of arguments among the experts. The goal is to achieve a homogeneous and consistent definition and explanation of the phenomenon in question as well as a clarification of dissenting views.

The *reflective discourse* deals with the interpretation of facts, with the clarification of knowledge ("state of the art"), the assessment of preferences and values and with the normative evaluation of issues and proposals for improvement. Reflective discourses are mainly appropriate as means to prepare decision-making and to resolve conflicts.

The *designing or planning discourse* is focused on the evaluation of options for action. Procedures of mediation and direct citizen participation belong to this category as well as conflict mediations among operators, regulators and affected people. Political or economic advising committees who propose or evaluate political options, can be subsumed under this category.

The *educational discourse* is not a discourse in the strict sense because it differs from the ideal model of discourse on account of a clear hierarchy between educator and participants. Nevertheless, it seems to be justified to include this category because the educational discourse has distinct discursive features: mutual learning, mutual understanding, reflection of empathy, and constant feed-back. The results of the other three discourses function as background material for and information input to the educational discourse.



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ON 'PRECAUTIONARY' AND 'SCIENCE BASED' APPROACHES TO RISK ASSESSMENT AND ENVIRONMENTAL APPRAISAL

Contents

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April 1999

1. EXECUTIVE SUMMARY

Both on the grounds of their physical magnitudes and in terms of their cultural and political connotations, the dilemmas and tensions encountered in the regulation of technological risks lie at the heart of modern politics. The Precautionary Principle has emerged as a diffuse body of ethical norms, analytical criteria and normative prescriptions and has rapidly become bound up in the practical business of regulation at national and international level. As its profile and influence has grown in the policy making arena, with ever more substantive and far-reaching implications, so the precautionary approach has become increasingly strongly contested. In particular, both in principle and in practice, the concept of precaution has in some quarters been seen to undermine the role of 'sound science' in the regulation of technological risk. As part of a wider inter-disciplinary project and drawing principally on the risk and environmental impact assessment literature, the present field study examines the practical implications for regulatory appraisal of this dichotomy between 'science' and 'precaution'.

The report first establishes the general implications of the Precautionary Principle in regulatory policy, briefly surveying the conditions under which a precautionary approach is held to be applicabe and reviewing the wide variety of instruments by means of which it might be implemented. Here many of the core difficulties in operationalising a Precautionary Principle are found to be held in common with the more orthodox procedures of 'science-based regulation' with which a precautionary approach is often contrasted. The report then goes on to examine in detail two fundamental problems in regulatory appraisal: *ignorance* ("we don't know what we don't know") and *incommensurability* ("we can't compare apples and oranges"). The scientific status of both concepts is explored. Focusing on the practical cases of energy technologies, chemicals and genetically modified crops, they are shown not only to present serious practical difficulties in the regulatory appraisal of technology, but also to challenge the notion that a sound scientific approach can be implemented solely by means of conventional analytical techniques such as risk assessment. Indeed, it is concluded that the imperatives both of 'sound science' and of 'precaution' actually identify similar practical responses to these problems in regulatory appraisal.

The specific practical measures which are suggested by this analysis to offer both precautionary and rigorously scientific responses to the dilemmas of regulatory appraisal are as follows:

- Broaden the scope of the regulatory appraisal of technological risk to include complex, synergistic and indirect effects as well as the associated public benefits.
- Acknowledge the intrinsically subjective character of the assumptions adopted in the framing of analysis.
- Maintain a culture of humility in the face of the many sources of uncertainty and ignorance in appraisal, expressed by means such as 'ignorance audits', 'error margins' and 'minimax criteria'.
- Complement and inform analysis with procedures for inclusive deliberation by stakeholders, such as consensus conferences citizen's juries, focus groups and deliberative polls.
- Conduct appraisal on a comparative rather than a case-by-case basis, including account of a variety of technological and policy options and the cumulative effects across different cases.
- Harness the potential of well-established straightforward multi-criteria appraisal techniques as a way of combining technical issues and fundamentally subjective matters of value judgement.
- Express appraisal results not as single discrete numerical values, but using sensitivity analysis systematically to 'map' the consequences of different value judgements and framing assumptions.
- Prioritise the qualities of transparency and simplicity in selecting appraisal methods and provide for effective extended peer review.
- Focus appraisal on the dynamics of portfolios of technologies rather than on individual options.
- Take account of qualitative strategic factors in technological strategies (like flexibility, reversibility and resilience).
- Allow iteration, reflexivity and open-endedness in the interactions between sustained scientific monitoring, continued analysis and inclusive deliberation in appraisal.
- Uphold the primacy of institutional legitimacy and political accountability in the final justification of regulatory decisions.

2 INTRODUCTION

2.1 The New Politics of Risk

According to an influential body of thought in the social sciences, modern industrial civilisation at the end of the Twentieth Century has seen the advent of the 'Risk Society'. Under this view, the abstract concept of risk has become a dominant ordering principle, helping to structure and condition social and institutional relations and, to some extent, replacing monetary wealth and cultural privilege as the focus of distributional tensions and political conflict [1]. Divergent values and interests together with issues of trust, rights and legitimacy in the regulation of risk are beginning to assume at least as much importance as the more traditional scientific and technical connotations.

Despite the theoretical complexities, the practical implications are almost too obvious to spell out: climate change, the ozone hole, urban smog, nuclear waste, pesticides, hormone disrupting chemicals, BSE, Brent Spar, genetically modified food. A host of intractable risks clamour for attention, threading their way in and out of the headlines at a frenetic pace. The issues quickly become polarised. Throughout the industrialised world, public confidence in the competence and intentions of those formally charged with the governance of risk is at a low ebb [2]. Reassurances on the part of government or industry are increasingly coming to be seen as little more than cynical exercises in financial or political damage limitation. There is a danger that public anxieties over each successive 'revelation' of technology-induced threat will compound into a corrosive general attitude of fatalism, disillusion and distrust.

Amidst the social, political and economic tensions, the physical parameters of risk management are truly impressive in their own right. Even if attention is restricted to the energy, chemicals and bio-technologies which form the focus of the present report, the scale of the challenge is formidable. Unless radical reductions are effected in the world-wide dependency on fossil fuels over the next few decades, it is a matter of scientific consensus that we face the potential for changes in global climate of a magnitude not experienced since the end of Ice Age [3]. Yet a wholesale shift to nuclear power would raise daunting challenges of its own, for instance compounding the need for effective management of highly radio-toxic materials for unprecedented spans of time [4]. In the field of chemicals regulation and licensing, the institutions of risk management are faced with some 10 – 15 million substances in commercial use, of which between 50,000 and 100,000 are variously recognised to be of regulatory interest [5]. Testing procedures which are acknowledged to be costly, slow and incomplete are proving inadequate in the face of the hundreds of new chemicals annually entering world markets [6]. And, most recently, the introduction of technologies for the genetic modification of agricultural crops has seen the advent (or intensification) of a variety of concerns ranging from possibilities of irreversible transformations in the genetic composition of established crops, wild plants or microbial life, to the potential fostering of pest resistance, dependence on herbicides, antibiotic resistance and even the creation of new food allergies nutritional effects or toxic

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1 Eg: Giddens, 1990; Luhmann, 1991; Beck, 1992; Lash, Szerszynski and Wynne, 1996.

2 Marris et al, 1996; Grove White et al, 1997

3 IPCC, 1996.

4 Evans, 1986.

5 Danish Board of Technology, 1996:7,20

6 Danish Board of Technology, 1996; OECD, 1993b.

reactions [7]. The novelty of the technologies and the diffuse, diverse and dynamic contexts for their application render such concerns extremely difficult to verify or falsify in advance of their manifestation.

With mounting institutional and economic commitments to global technological infrastructures in all these areas, the stakes are high and growing ever higher. Innovation proceeds at an unremitting pace. Once a particular industrial strategy or technological path has been chosen, a host of self-reinforcing mechanisms come into play. The enormous investments of human resources, financial capital and institutional reputation can render technological trajectories – once taken – effectively irreversible. The world-wide experience of nuclear power illustrates the enormous costs to all concerned of (depending on your view) over-ambitious expectations, belated critical questioning or a premature 'loss of nerve' on the part of society as a whole. On the other hand, a failure to seize the initiative and harness the positive creative potential of science and technology can lead to foregone opportunities, economic stagnation and even defeat in the face of the many challenging problems of the modern world.

The question is: what road to take? Whether they result from technological hubris or a post-modern crisis of confidence, mistakes in either direction can be effectively irreversible and extremely costly. There is agreement on all sides of the debate that the more profound and pervasive long term dimensions of technological risk cannot be left to 'the market' alone to resolve. Private enterprise, consumers and public interest groups alike seek consistency, clarity and decisiveness on the part of government (and, increasingly, inter-governmental) regulatory institutions. But how are such qualities to be achieved amidst the messy and intractable complexities and uncertainties of the emerging 'Risk Society'?

It is against this daunting background that the current debate is played out over the respective roles of 'precaution' and 'science' in the regulation of technological risk. Through all the furore, the day to day regulation of technologies must labour on. The practical business of risk assessment and environmental appraisal continues to play an essential role and one which is not necessarily assisted by the wider social and political overtones of the risk debate. It is the purpose of the present project to explore some of the profound implications for regulatory appraisal of contending visions of 'precaution' and 'science'.

[7] Eg: Royal Society, 1998; Wheelis et al, 1998

2.2 'Precaution' and 'Science Based Regulation' in the Management of Technological Risk

Arising repeatedly in different guises since the 1972 Stockholm Environment Conference [8] and finding its first coherent formal shape in the *Vorsorgeprinzip* adopted in German environmental policy in the early 1980's [9], the Precautionary Principle has become a potent and pervasive concept throughout the entirety of the modern environment debate [10]. One of the broadest and most globally influential formulations is Principle 15 in the 1992 Rio Declaration on Environment and Development:

> "*In order to protect the environment, the precautionary approach shall be widely applied by States according to their capabilities. Where there are threats of serious or irreversible damage, lack of full scientific certainty shall not be used as a reason for postponing cost-effective measures to prevent environmental degradation*" [11]

Perhaps the most longstanding and substantive discussions of the practical implications of precaution have taken place in the field of marine pollution, where successively more robust conclusions have been arrived at over the years during international negotiations under the auspices of bodies such as the London Convention, Oslo and Paris Commissions and the North Sea Ministers Conference [12]. Under the terms of the 1992 OSPAR Convention, for instance, the Precautionary Principle is interpreted to mean that "*preventive measures*" are to be taken "*when there are reasonable grounds for concern even when there is no conclusive evidence of a causal relationship between inputs and their alleged effects*" [13].

In this vein, discussions over the practical implementation of a Precautionary Principle in policy making have extended into fields such as the climate change negotiations, chemical regulation and the licensing of environmental releases of genetically modified organisms. It is defined in the 1992 Framework Convention on Climate Change, for instance, in the following terms:

> "*The Parties should take precautionary measures to anticipate, prevent or minimise the causes of climate change and mitigate its adverse effects. Where there are threats of serious or irreversible damage, lack of full scientific certainty should not be used as a reason for postponing such measures, taking into account that policies and measures to deal with climate change should be cost effective so as to ensure global benefits at the lowest possible cost*" [14].

Likewise, though not named as such, a precautionary formulation is incorporated into the preamble of the 1992 Biodiversity Convention, to the effect that:

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[8] Cameron and O'Riordan, 1994b

[9] Boehmer-Christiansen, 1994

[10] See articles in Cameron and O'Riordan, 1994a

[11] Principle 15, UNCED, 1992

[12] Hey, 1991, 1992; RCEP, 1998.

[13] Article x: OSPAR, 1992

[14] FCCC, 1992

> "*…where there is a threat of significant reduction or loss of biological diversity, lack of full scientific certainty should not be used as a reason for postponing measures to avoid or minimise such a threat*" [15].

It has been argued that the provision for 'case by case' and 'step by step' approval procedures under the 1990 EC Directive on the deliberate release of genetically modified organisms [16] constitutes the first piece of international legislation in which the Precautionary Principle is translated into precautionary regulation [17]. However, over the ensuing years, interpretations of the practical implications of the Precautionary Principle in international environmental regulation have moved on. The recognised scope of the concept has broadened and the public and political profile and institutional and economic stakes have all increased. Under the terms of the 1995 Esbjerg Declaration, for instance, environment ministers of North Sea states confirmed the adoption of precaution as a guiding principle, holding this to imply

> "*continuously reducing discharges, emissions and losses of hazardous substances … moving towards the target of their cessation within one generation (25 years) with the ultimate aim of concentrations in the environment near background values for naturally occurring substances and close to zero concentrations for man made synthetic substances*" [18].

Such developments have profound repercussions for the governance of technological risk in areas far removed from the regulation of the pollution of the North Sea. The wide-ranging review of chemical policy in the EU undertaken in 1998, for instance, saw many member states advocating precautionary measures including a halt to the use of all irreversibly toxic, persistent or bioaccumulative substances and a shift in the burden of proof in the licensing process to require proof of harmlessness from manufacturers before the release of products onto the market [19].

As is inevitably the case with any broad principle with such wide-ranging implications in such a heavily contested policy arena, the question of the validity and utility of the Precautionary Principle has become entangled in the intensive and often polarised interplay of divergent socio-political interests and perspectives. This has not always been conducive to measured, focused or constructive discussion. One of the most prominent axes for the emerging debate over the Precautionary Principle concerns a contrast that is often drawn between 'precaution' on the one hand and 'science based regulation' on the other. The implication of this distinction is that the adoption of a precautionary approach might somehow be seen *a priori* as being antithetical to – or at least in tension with – the principles of scientific rigour [20].

Under such a view, the implementation of the Precautionary Principle becomes essentially a politically-determined compromise on what are held to be the otherwise clear dictates of the 'sound science' of risk assessment [21]. Other perspectives strenuously deny such a dichotomy, holding that a Precautionary Principle is neutral with respect to the scientific status of a body of knowledge, relating only to the practical

[15] Preamble, Biodiversity, 1992.

[16] EC, 1990

[17] Von Schomberg, 1998b

[18] Esbjerg, 1995

[19] ENDS Report 279 4/98.

[20] Eg: Chapman, 1997

[21] For instance, interventions to the Royal Society / Times Higher Education Supplement conference on '*Science, Policy and Risk*' on 19 March 1997 (audio transcript on the World Wide Web at http:\\.thesis.newsint.co.uk). The general perspective underlying such attitudes is admirably expressed by Wolpert (1992).

harnessing of this knowledge for regulatory purposes [22]. Still others argue that the adoption of a principle of precaution constitutes the most scientifically rigorous way of framing and interpreting the results of scientific models for incorporation in the policy process [23]. Whatever position is taken, it is clear that even the very framing of discussion of science and precaution is intrinsically laden with highly charged assumptions and implications.

[22] Eg: O'Riordan and Cameron, 1994.

[23] Eg: Johnston, et al, 1998; Santillo et al, 1998.

2.3 The Scope and Structure of this Project

It is the aim of the present project to explore, in an open-minded and interdisciplinary fashion, some of the key issues arising in discussions of precaution and science in the regulation of technological risk, with particular reference to the regulation of energy and genetic modification technologies and somewhat less intense attention to chemicals policy. Within this overall framework, the present work examines the implications for discussions of 'precautionary' and 'science-based' regulation arising in the fields of risk assessment and environmental appraisal. The arguments and information set out in the present paper draw on an earlier discussion paper and scoping paper and will be further developed in a subsequent 'field study' before finally being integrated with the conclusions arising in three sister 'field studies' examining perspectives (respectively) from the fields of (i) formal decision analysis and economics, (ii) institutional and regulatory policy analysis and (iii) the social study of science and constructive technology assessment.

Following this introduction to the general background for the emergence of the Precautionary Principle, the next part of this study (Part 3) explores the practical implications of the Precautionary Principle, both in terms of the conditions under which it is variously thought to be applicable and in terms of the instruments by means of which it can be implemented. Based on this discussion and focusing on the particular topic of risk assessment and environmental appraisal, a series of general difficulties are then identified in the operationalising both of 'precautionary' and 'science-based' approaches to the regulatory appraisal of technologies.

This then forms the basis for the focusing of discussion on the main topic of this paper – the implications for risk assessment and environmental appraisal procedures. The series of general difficulties identified in Part 3 are addressed in terms of two underlying problems in regulatory appraisal. These are explored in the Parts 4 and 5, first in terms of their scientific status and then in terms of their practical importance for the appraisal of energy technologies, chemicals and genetically modified crops. In Part 6, a series of practical responses to these problems are briefly discussed and argued to offer a way of implementing not only 'sound science' but also 'precaution' in the regulatory appraisal of technology.

It is not possible in a project of this sort comprehensively to cover all the pertinent issues, still less to satisfy all perspectives. In focusing on risk assessment and environmental appraisal, many of the most important general features of 'precautionary' and 'science based' regulation touched on in the next section will not be further developed in this report. However, as a complement to the highly detailed discussions underway within individual sectors and disciplines it is hoped that the present project may make a contribution towards the drawing of some broad practical conclusions concerning the best means to carry forward the regulatory appraisal of technological risk both in terms of scientific and precautionary imperatives.

3 GENERAL IMPLICATIONS OF THE PRECAUTIONARY PRINCIPLE

3.1 Introduction

In a seminal early critique of the Precautionary Principle, the US environmental lawyer Daniel Bodansky voiced concerns that are still shared by many involved in the business of environmental regulation. He argued that "[a]lthough the Precautionary Principle provides a general approach to environmental issues, it is too vague to serve as a regulatory standard because it does not specify how much caution should be taken. In particular, it does not directly address two key questions: When is it appropriate to apply the Precautionary Principle? And what types of precautionary actions are warranted and at what price?".

This distinction between issues of *diagnosis* and issues of *prescription* makes a useful starting point for any investigation of precaution and science in the regulation of technological risk. Under what sort of conditions is it felt appropriate (under different perspectives) to apply the precautionary principle? And when it is applied, what types of precautionary actions are warranted and at what price? Each of these questions will briefly be taken in turn in this section in order to provide a background to the more detailed discussion of the practical implications in the fields of risk assessment and environmental appraisal.

3.2 Diagnosis: under what conditions might a Precautionary Principle be applied?

The Precautionary Principle is variously held to be applicable under the following conditions:

- Where uncertainties are cited as grounds for delay in regulatory intervention, effectively placing the burden of proof on those who seek to demonstrate environmental harm, rather than on those favouring the policy, investment or technology options held to cause that harm [24].
- Where the regulatory framework focuses disproportionately on the control or treatment of environmental burdens, rather than on their anticipation and prevention [25].
- Where regulation is predicated on the basis of notions of 'assimilation' or 'carrying capacity' in particular environmental media, where manifestly complex nonlinear environmental systems are conventionally understood in terms of linear models, or where crucial aspects of the effects in question are recognised to be irreversible or long-term in their manifestation [26].
- Where stochastic modeling techniques are routinely employed, despite grounds for doubt over the adequacy of the underlying monitoring or other uncertainties over the basis for the associated probabilistic data or over the completeness or realism of the set of possible outcomes and contingent circumstances included in analysis for appraisal [27].

[24] Shackley et al, 1998; Lindsay, 1995, Gray, 1994; Wynne, 1996.

[25] Wynne, 1992; Tickner, 1998; Hey, 1991; Jackson and Taylor, 1992.

[26] Jackson and Taylor, 1992; Lindsay, 1995; Dovers and Handmer 4245; Tickner, 1998.

[27] Perrings, 1991; Johnston et al, 1998; Santillo et al, 1998.

- Where questions are raised by the sheer diversity of burdens associated with the activities in question or by the possibility of synergistic effects involving other environmental agents not necessarily directly related to the activity in question [28].
- Where at least some of the environmental effects in question are held to display specific properties such as carcinogenicity, mutagenicity, teratogenicity, or (more broadly) persistent toxicity or a tendency to bioaccumulate, or (most generally) involve release to the environment of any synthetic material or natural material in unnatural concentrations [29].
- Where activities would prove impossible to insure commercially in the absence of dedicated liability legislation [30].
- Where important public constituencies display a pronounced lack of trust in the institutions responsible for developing, marketing or regulating the options in question [31].
- Where formal procedures for social appraisal are held to be unduly closed, circumscribed in scope or otherwise constrained, where there exist pronounced asymmetries in the information available to different parties in the regulatory process or where commercial or regulatory decision makers are held to have displayed a manifest lack of capacity to learn from previous adverse experience [32]
- Where there exist strong interdisciplinary barriers or antagonisms, or where the scientific communities associated with the appraisal of particular effects express results with undue certainty or precision, are unwilling to acknowledge limitations in the relevant bodies of knowledge, or deny the negotiability of assumptions concerning the framing of analysis [33].
- Where the scale or nature of the effects in question are subject to pronounced geographical or demographic variability or are otherwise seen to be unevenly distributed across affected populations, where they are transboundary in extent or held to affect the global commons [34].
- Where questions are raised over the degree to which the options in question are actually justified (in terms of the functions or aims declared by their sponsors) or where certain alternative options delivering similar ends are held to have been unduly excluded [35].
- Where there is a marked mismatch between the timescales which are characteristic of decisions regarding the options in question and those displayed by the associated legal, administrative or regulatory processes - for instance where a technology is subject to a particularly rapid developmental trajectory [36].

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[28] Johnston et al, 1998; Santillo et al, 1998.

[29] Johnston et al, 1998; Danish Board of Technology, 1996; Jackson and Taylor, 1992; Bodansky, 1991.

[30] Perrings, 1991.

[31] Wynne, 1996; Jordan and O'Riordan, 1998.

[32] Jordan and O'Riordan, 1998; Freestone, 1994; Gray, 1994; Wynne, 1996.

[33] Earll, 1994; Jordan and O'Riordan, 1998; Wynne, 1992.

[34] Mayer, 1994; Earll, 1994; Jordan and O'Riordan, 1998.

[35] Wynne, 1992; Freestone, 1994; Craig, 1994; Gray, 1994; Mayer, 1994; Jordan and O'Riordan, 1998.

[36] Earll, 1994.

3.3 Prescription: by what means might a Precautionary Principle be implemented?

The implementation of a Precautionary Principle is variously held to involve (or, at least, imply consideration of) some sub-set of the following range of characteristics:

- A general approach embodying greater humility in acknowledging the limitations of science, the vulnerability of the natural environment; the rights of the victim, the availability of technical alternatives, the complexity of behaviour in real organisations, the variability of local and other contextual factors, the plurality of equally-legitimate value judgements adopted by different groups in society and the necessity of adopting long term, holistic and inclusive perspectives in appraisal [37].
- The accommodation of subordinate principles such as 'prevention' (a duty to prevent rather than to control or treat emissions) [38], 'polluter pays' (the placing of burdens on all parties responsible for, or benefiting from, damaging activities) [39], 'no regrets' (a presumption in favour of actions simultaneously satisfying economic, environmental and wider social criteria) [40], 'clean production' (the adoption of only those investment, technology or policy options which are demonstrably of lowest impact) [41] and a 'biocentric ethic' (recognising the intrinsic value of non-human life) [42].
- The appraisal and choice of technology, policy and investment options and decisions over their justification, implementation and regulation should take account of a full range of pertinent alternatives (including complete inaction) and should be subject to participatory procedures for prior consultation and open negotiation involving all interested and affected parties [43]. The definition of crucial concepts such as 'clean technology' or 'best practicable environmental option' in any given practical context demands freedom of information, transparency, inclusiveness and extended peer review in the working of scientific panels [44]. Freedom of information and transparency also imply the provision of substantive information to consumers and end-users by means of audited labeling schemes [45].
- The framing assumptions adopted in analytical appraisal (using techniques such as multi-criteria, environmental impact, comparative risk and cost-benefit analysis) should be subject to validation and continuous evaluation by prior procedures for wider participatory deliberation (such as consensus conferences, scenario workshops and citizens juries). Both analytical and deliberative appraisal should

[37] Jordan and O'Riordan, 1998; Tickner, 1998; Dovers and Handmer, 1992; Freestone, 1994; Gray, 1994; Mayer, 1994; Hey, 1992; Jackson and Taylor, 1992; Wynne, 1996; Wingspread, 1998; MacGarvin ; 1995; Johnston et al, 1998; Hey, 1991.

[38] Tickner, 1998.

[39] Tickner, 1998; Costanza and Cornwell, 1991.

[40] Dovers and Handmer, 1992.

[41] Hey, 1991; Jackson and Taylor, 1992; Johnston et al, 1998; Freestone, 1994; Earll, 1994; Tickner, 1998; MacGarvin , 1995.

[42] Jordan and O'Riordan, 1998.

[43] Freestone, 199; Mayer, 1994; Wingspread, 1998; Tickner, 1998; Jackson and Taylor, 1992; MacGarvin, 1995.

[44] Hey 1991.

[45] Ecocycle, 1997a; Ecocycle, 1997b.

be conducted such as to maintain independence from sponsors and framed such as to address all options and their respective effects and the totality of the 'life cycles' of all associated products, facilities and materials, including long term, non-linear and synergistic factors. Here, the practice of discounting future effects is particularly problematic. Results of analysis should be expressed in terms of sensitivities to uncertainty bounds and divergent framing assumptions (such as those concerning behavioural aspects) [46].

- The treatment of uncertainty in appraisal is a subject of particular importance. This will necessarily involve procedures for ensuring the allowance of a 'margin of error' (in favour of the environment) [47] and an emphasis on deterministic 'sensitivity envelopes' (derived through propagation of 'worst case' parameter and variable values) [48] rather than elaborate stochastic modeling. However there is a recognised need for novel heuristics and techniques for handling decision-making under intractable uncertainties and ignorance. Candidate approaches include the conduct of 'ignorance audits' (based on various taxonomies for the forms and sources of ignorance) [49], the implementation of 'minimax' criteria (focusing on the minimising of worst case outcomes) [50] and the maintenance of 'diversity', 'flexibility' and 'resilience' in technology and policy options through pro-active approaches based on openness and adaptation in the face of dynamic and unpredictable operating environments [51].

- A fundamental feature of the implementation of the Precautionary Principle in international and domestic regulatory instruments is that "lack of evidence of harm is not the same as evidence of lack of harm" [52]. This involves changes in legal presumptions and the standard of proof, requiring the adoption of a 'reverse onus' in favour of the environment [53]. Far from being seen as 'unscientific' such a procedure already applies in the licensing of pharmaceuticals, where there is a requirement for prior justification and standards of proof for the absence of harm [54]. Where prevailing environmental regulatory provisions are permissive in character, this means a shift away from a *status quo* under which the burden of proof is higher for changing an incumbent understanding than for sustaining it [55]. In practice, this may be implemented in international law by clarifying and standardising the basis for action (for instance, by imposing on all parties the measures of the most precautionary party), by majority voting (which would remove the effective veto enjoyed by the least precautionary party) and by comprehensive prior consultation procedures (for approval of the activities in question by individual states party) [56].

- At the domestic level, legislation may embody provisions such as 'safe minimum standards' (the imposition of back-stop safeguards based on whichever is the stricter among health or environmental

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46 Earll, 1994; Freestone, 1994; Gray, 1994; Mayer, 1994; CA, 1998; Jordan and O'Riordan, 1998; Tickner, 1998.

47 Jordan and O'Riordan, 1998.

48 Gray and Bewers, 1996.

49 Dovers and Handmer, 1992.

50 Perrings, 1991.

51 Faber and Proops, 1994; Collingridge, 1982; Stirling, 1994.

52 Wynne, 1996.

53 Lindsay, 1995; Gray, 1994; Wynne, 1996; Jackson and Taylor, 1992; Freestone, 1994; Mayer, 1994; Earll 1994; Jordan and O'Riordan, 1998; Wingspread, 1998; Tickner, 1998; Hey, 1992.

54 Lindsay, 1995.

55 Shackley et al, 1998.

56 Dovers and Handmer 4245; Cameron and Abouchar, 1991; Hey, 1991.

models) [57], 'reverse listing' (under which only specified activities are permitted) [58] and the adoption of time-tabled 'forcing targets' (derived by 'back-casting' bans or phase-out schedules) [59]. These may involve 'evidentiary presumptions' (citing properties such as persistence, toxicity and bioaccumulation as proxies for unacceptable environmental impact) [60]. They may also involve provisions establishing the responsibility of the individual decision maker (such as those reportedly enacted in New Zealand [61]). Where the effect is not to undermine the precautionary character of regulation, such measures may readily include 'incentive-based' economic instruments such as 'green taxes' and 'tradable permits' [62].

- Dedicated provision for the efficient, timely and equitable compensation of those suffering damage as a result of an activity and ensuring the sharing of burdens across all responsible parties [63]. This may include various forms of product 'take back' schemes [64] along with instruments upholding the liability of the operators or beneficiaries of an activity (such as the channeling of liability to investors, financiers, suppliers or contractors) [65]. This is likely to be associated with a shift away from fault-based liability towards a 'strict' or even 'absolute' liability regime, with associated implications for the burden of proof (eg: exoneration under a 'strict' regime requires demonstration of 'due diligence'). Mandatory insurance capacities or flexible financial measures may be considered, such as 'restoration requirements', 'deposit-refund schemes', 'assurance bonds' or 'environmental product insurance' to provide prior segregated funding for eventual decommissioning and restoration or 'worst case' compensation and remedial action if and when this proves necessary) [66].
- The adoption of regulatory and management practices such as 'waste prevention audits', 'duty of care', 'total quality management' and 'continuous performance improvement' which integrate the appraisal and administration of burdens across different environmental media and industrial sectors [67]. Here, there is a crucial commitment to long term surveillance and monitoring, with direct feedbacks to regulatory and management practices. Educational programmes within industry, government and the wider society are also of crucial importance [68].
- Finally, the strongest formulation of a '*Principle of Precautionary Action*' holds as its aim the avoidance of inputs into the environment of unnatural substances, or of natural substances in unnaturally large quantities, so far as is 'ecologically sensible'. Such a notion of 'ecological sensibleness' addresses economic factors as a sub-system of the environment and implies that preventing a release to one environmental medium will not lead to damage to another and that, in

[57] Earll, 1994; Dovers and Handmer, 1992.

[58] Freestone, 1994; Danish Board of Technology, 1996; Santillo et al, 1998.

[59] Earll, 1994; Tickner, 1998.

[60] Dovers and Handmer, 1992; Cameron and Abouchar, 1991; Bodansky, 1991.

[61] Earll, 1994.

[62] Costanza and Cornwell, 1991.

[63] Jordan and O'Riordan, 1998.

[64] Ecocycle, 1997.

[65] Costanza and Cornwell, 1991; Wingspread, 1998; Jordan and O'Riordan, 1998; Earll, 1994; Freestone, 1994.

[66] Earll, 1994; Freestone, 1994; Dovers and Handmer, 1992; Costanza and Cornwell, 1991.

[67] Freestone, 1994; Earll, 1994.

[68] Mayer, 1994; Gray, 1994; Lindsay, 1995; Johnston et al, 1998, MacGarvin, 1995; Hey, 1991; Tickner, 1998.

practice, substances should be prioritised for action in relation to their liability to cause harm [69]. An approach on these lines is currently actively under discussion by regulatory bodies in certain EU member states [70].

3.4 Some Difficulties in the Operationalising of 'Precaution' and 'Science Based Regulation'

Attempts to set out the formal connotations of any general principle are inevitably subject to question. Such is arguably the case even with long-established single-disciplinary concepts such as 'economic efficiency'. It is certainly true of emerging and innovative multi-disciplinary notions like 'precaution', especially where they are central to highly charged political debate and large scale economic interests. Many apparent contradictions, ambiguities and begged questions will already be evident to the reader. For the purposes of the present interim report, however, the issues highlighted in this section are those which appear to be most important not only for the operationalising of precaution, but also for the operationalising of the interlinked theme of 'science-based regulation'. In this regard, particular difficulties are experienced (both in diagnosis and in prescription) under the following circumstances:

- Questions may be raised concerning the core issue of precaution – the treatment of uncertainty. Here, there seems to be little discussion in the literature of the handling of *non-environmental* uncertainties. The social appraisal and regulation of technology, policy and investment options must necessarily address factors such as equity, employment and wider economic considerations – many of which may display uncertainties which are no more tractable than environmental uncertainties. Adoption of a symmetrical principle of precaution in the face of these uncertainties may conflict with an approach focusing exclusively on the environment.

  The appropriate handling of uncertainty is at least as much (or even more) an open problem in 'science based regulation' as it is under the 'precautionary principle'. To what extent are probabilistic or risk-based characterisations of incertitude practically useful – even in their own terms? What might be more appropriate decision making heuristics under conditions of more intractable uncertainty and 'ignorance', where the tools of probability theory, risk assessment (and even scenario analysis) are formally inapplicable?

- To what extent are private cost and wider economic factors taken to be adequately addressed in formulations such as 'ecologically sensible', 'best available technique', 'best practicable means' and 'clean production'. How do we go about establishing the economic value of a given level of precaution? How can we ensure that regulatory interventions are 'proportionate' to the impacts they are intended to forestall?

  Although relatively rarely acknowledged, directly analogous problems are encountered in the orthodox procedures of 'science based regulation'. What is the economic value of the 'risks' or environmental or health 'externalities' avoided by a given regulatory intervention? How are divergent values and distributional issues to be addressed?

- Choices are often not simply between risk or caution, but in terms of one form of risk or another. Although central to concepts such as 'clean production', the literature on the Precautionary Principle seems to give little attention to the handling of trade-offs between different forms of environmental effect.

  These issues of aggregation and trade-offs are scarcely less pertinent with respect to 'science-based regulation', under which techniques such as risk and cost-benefit analysis fail to resolve serious

[69] Jackson and Taylor, 1992.

[70] For instance, in Sweden, cf: ENDS 281 6/98; 269 6/97.

problems with the inter-comparison of incommensurable types of effect and the broad applicability of singe metrics such as mortality or monetary value.

- The operationalising of precaution in terms of the identification of a 'best available technique' (or, for that matter, of a 'clean technology') in any given context raises serious scope for dispute over the appropriate way of framing the various investment, technology or policy options in question. Should they be alternatives at the level of the individual process (eg: 'bolt-on' or 'end-of-pipe' options), sector (eg: alternative bottom-up designs for plant) or function (eg: demand management versus supply-side options or radically different technologies).

  Similar difficulties of framing and 'system boundaries' affect the more orthodox procedures of 'science-based regulation'.

- Technologies (no less than policies) are not generated in a 'black box'. They are the products of complex interactions between physical necessities, individual perceptions, institutional interests and market incentives. The process of regulation itself (whether of a 'precautionary' or more conventional character) is an important reflexive factor in the process of technological and political innovation. How can the social processes of regulation and innovation be better integrated?

- Both with respect to 'precaution' and 'science-based regulation', there are serious questions over what might be called the 'politics of acceptability'. What technological or policy options – and what associated levels of 'risk' or 'environmental harm' – may be held to be 'acceptable' in any given context? How might a plural democratic society go about arriving at shared understandings on such contentious issues?

- How are appraisal and regulation (both 'precautionary' and 'science-based') to address the current 'crisis of confidence' in public attitudes to the positions taken on technological risk by government and industry institutions? By what means can the current levels of polarisation be reduced in discourses such as those concerning energy production or genetic modification in agriculture? How can regulation at the same time accommodate divergent public perceptions and the relatively consensual understandings of the scientific establishment? How can we at the same time achieve rigour and legitimacy in the articulation of 'facts' and 'values'

- The debates over 'precaution' and 'science based regulation' are replete with benign-sounding concepts such as 'flexibility', 'reversibility', 'diversity', 'adaptability', 'resilience' and 'robustness'. How might we go about operationalising those concepts which are practically applicable in the context of real industrial strategies, technological trajectories and regulatory imperatives?

3.5 The Implications for Risk Assessment and Environmental Appraisal

Having reviewed the broad background to the diagnoses and prescriptions generally associated in a variety of fields with the Precautionary Principle, it now remains to explore the central problems of implementation which were identified in the last section to be held in common both by ‘precautionary’ and ‘science-based’ approaches to the regulatory appraisal of technological risk. In doing this, the scope of the discussion will be focused in two ways. First, attention will concentrate on the implications for regulatory appraisal (ie: risk and environmental impact assessment) rather than on the broader areas of regulatory policy such as governance, institutions, instruments, monitoring and compliance. Second, practical examples will be provided by reference to the cases of energy (especially electricity supply) technologies and genetically modified crops, with somewhat less detailed examples drawn from the regulation of chemicals.

The starting point for the ensuing discussion is that the general difficulties of uncertainty, trade-offs, framing, innovation and the politics of acceptability and trust identified here to apply both to ‘precautionary’ and ‘scientific’ approaches might actually be seen to relate to two more fundamental problems: *ignorance* (“we don’t know what we don’t know”) and *incommensurability* (“we can’t compare apples and oranges”). These problems are quite well known (and even intuitively obvious) in different guises, but are usually discussed in terms which relate only tangentially to questions over their ‘scientific’ status. In the sections which follow, it will be argued that these deep-seated problems are actually founded, not in a critique of science in appraisal, nor in a dichotomous opposition of ‘science’ and ‘precaution’, but in some of the most well-established principles of scientific rigour in the theory of risk assessment and rational choice.

4 PROBLEMS IN REGULATORY APPRAISAL (1): IGNORANCE

4.1 The Scientific Status of the Condition of 'Ignorance'

A concern with the proper treatment of 'incertitude' [71] lies at the heart both of scientific and of 'precautionary' approaches to the regulation of technological risk. However, there is in some quarters a tendency to assume that a 'sound scientific' approach is synonymous with the adoption of a probabilistic paradigm. Under such perspectives, all situations of incertitude may be treated as if they were a problem of 'risk' in this narrow sense of the term. In this view, the pursuit of 'science based regulation' can appear to be synonymous with a reliance on the methodologies of risk assessment in appraisal. Additional provisions for 'precaution' in regulatory appraisal can thus appear as redundant, inefficient or even counterproductive in their effect. It is in this light that this report will examine the relationship between 'risk-based' and 'precautionary' approaches to incertitude, first in theoretical and then in more practical terms.

In contemplating first the theoretical validity of the formal concept of 'risk', the starting point must be an examination of the degree to which this concept actually addresses the *full* character of incertitude in the real world. Figure 1 illustrates the twofold distinction between 'knowledge about likelihoods' and 'knowledge about outcomes' which is central to the probabilistic conception of 'risk' at the heart of the 'science-based regulation' . Recognising the potential for greater or lesser knowledge on each of these axes yields four fundamental categories of 'incertitude'. In the case of the formal concept of 'risk' itself (in the strict sense), then, we are in the top left-hand corner of the top left hand quadrant of Figure 1. Where there exist credible grounds for the assignment of a discrete probability to each of a well-defined set of possible outcomes, then a regulatory decision-maker (or process) faces the paradigm conditions of *risk* [72]. Classically, this may be taken to reflect established frequencies of occurrence of similar past events under comparable circumstances (or in a hypothetical series of trials). Where outcomes can be fully characterised under a single metric (such as mortality frequency), then probabilities may be expressed as a continuous density function over the chosen scale.

Such 'realist' or 'frequentist' probabilistic 'risk-based' understandings of incertitude are extremely powerful conceptual tools in dealing with completely-understood self-contained formal rule-based systems (such as games of chance), or highly repetitive events affecting a multitude of subjects in long term stable systems (as with life insurance in the absence of war, plague or famine) [73]. However, the epistemological basis for a more general 'realist' interpretation of the notion of probability has come under increasing doubt

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[71] For reasons of clarity that will become clear in the discussion below, the present author favours the use of the term 'incertitude' in a general overarching fashion which subsumes both 'risk' and 'uncertainty' in the strict senses of these terms as defined below.

[72] After Knight, 1921. See also Luce and Raiffa, 1957. This is sometimes referred to (eg: Rosenberg, 1996:340) as 'Arrovian uncertainty' (cf: Arrow, 1974b) to distinguish it from the 'Knightian uncertainty' described below and in Box 2.

[73] See Bernstein, 1996 for a lively account of the historic development of applications in these fields.

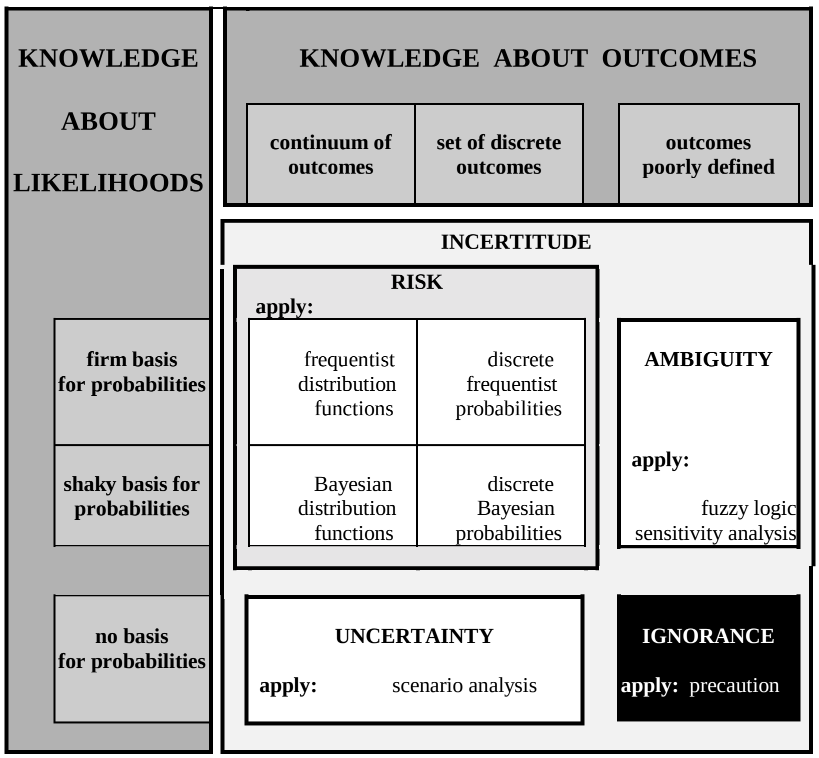
over recent years [74]. In particular, the validity of the underlying assumptions break down very rapidly in the context of the regulation of novel technologies, where conditions are far less tractable and circumscribed than those described above. The real-world systems impinging on the regulation of energy technologies, chemicals and genetically modified organisms, for instance, are imperfectly understood, open-ended, complex and dynamic. Serious doubts emerge over the crucial assumption of comparability between past and future circumstances and outcomes. Together, these features undermine the concept of a hypothetical series of trials which is so central to classical 'frequentist' notions of probability.

Moreover, where the different aspects of performance are many in number and incommensurable in form (as is again the case in regulating novel technologies), attempts to reduce such multidimensional qualities

[74] A trend recognisable in Hacking, 1975; Weatherford, 1982; Szekely, 1986; Watson, 1994; Porter, 1995.

to a single metric further compound the difficulties [75]. In disciplines such as financial investment appraisal, the existence of short time horizons and a dominating monetary 'bottom line' are often held to supersede such difficulties and justify the imposition of a single numeraire [76]. Yet, even in the field of financial management, it is evident that probabilistic approaches are more prominent in teaching and academic research than they are in real fund management strategies [77]. In fields such as environmental appraisal and technology assessment, these issues of scale, novelty, uniqueness, complexity, change, irreversibility and incommensurability are manifestly the norm and are even less readily set aside. In a strict 'frequentist' sense, then, techniques based on probability theory are quite simply inapplicable to many of the most important decisions over the regulation of technological risk. In these contexts at least (in the words of the celebrated probability theorist, de Finetti), "probability does not exist" [78].

Figure 1: The Formal Definitions of 'Risk', 'Uncertainty' and 'Ignorance'



Of course, the usual response to this familiar predicament is to adopt some more openly subjective 'Bayesian' perspective and regard probabilities as an expression of the 'relative likelihoods' of different

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75 A detailed discussion of the issues surrounding this concept of incommensurability is undertaken in Section 5 of this interim report.

76 Cf: Simha, Hemalatha and Balakrishnan, 1979; Lumby, 1984; Brealey and Myers, 1988.

77 Myers, 1984. See also: Malkiel, 1989.

78 De Finetti (1974) quoted in Morgan et al (1990:49)

eventualities, given the best available information and the prevailing opinions of specialists [79]. Yet, even this more modest approach requires heroic aspirations to complete information and exhaustive analysis concerning all possible options, outcomes and prior circumstances [80]. Such assumptions are still extremely difficult to justify in the face of the regulatory realities of global warming, novel chemicals or genetically modified organisms. Yet, even if the basis for specialist understandings were acknowledged to be complete and robust, there remain a host of more technical practical problems. The random variability assumed by standard error determinations is often overwhelmed by non-random influences and systematic errors [81]. The form of a probability distribution is often as important as its mean value or its variance. Where differing irregular or asymmetric probability density functions overlap, with potentially enormous implications for the apparent performance ordering of options [82]. In short, a 'Bayesian' extension of the probabilistic paradigm exchanges the positivistic hubris and restrictive applicability of the frequentist approach for enormous sensitivity to contingent and subjective framing assumptions. Under a Bayesian approach to risk assessment, narrowly divergent (but equally reasonable) inputs may yield radically different results.

Where these difficulties are recognised, a regulatory decision-maker (or process) confronts the condition of *uncertainty* in the strict sense introduced originally nearly eighty years ago by the economist Knight [83]. Here, we are in the lower left-hand quadrant of Figure 1. This is a situation where it is possible to define a finite set of discrete outcomes (or a single continuous scale of outcomes), but where it is acknowledged that there simply exists no credible basis for the assignment of probability distributions. Although advocates of probabilistic approaches sometimes reject this distinction between situations where probabilities are 'knowable' and those where they are 'unknowable' [84], such opposition often seems motivated more by a sentimental attachment to the facility and elegance of probability calculus than by any refutation of the practical depth and scope of incertitude in the real world [85]. Whatever the intent, the continued advocacy of techniques such as portfolio theory or expected utility maximisation under conditions of strict uncertainty can have the effect of introducing confusion over terminology [86] fostering quite fundamental misconceptions amongst non-specialists over the applicability and rigour of probabilistic approaches such as risk assessment. Indeed, the general treatment of uncertainty as if it were mere risk offers a prime example of what the Nobel laureate economist Hayek once lamented as the "pretence at knowledge" [87].

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79 Jaynes, 1986; Wallsten, 1986.

80 Collingridge, 1982:22.

81 Bailar, 1988. An example of this may be found in comparisons of the results obtained in probabilistic risk assessment studies of nuclear safety (Evans, 1986, discussed in more detail in Stirling, 1994)

82 Goodman, 1986; Beck, 1987.

83 Knight (1921), elaborated usefully many times since, eg: Luce and Raiffa, 1957.

84 The phrasing is that of Luce and Raiffa (1957).

85 For instance, on the somewhat expedient grounds that the distinction "serves little purpose" (Lumby, 1984:108), since it renders "the theory of probability virtually inapplicable to real world decision making, outside games of chance involving dice or cards" [Morgan et al (1990:49)]. Discussions of uncertainty tend all-too-often to be framed in terms of the available techniques, rather than the nature of the problems themselves (eg: Andrews, 1995).

86 For instance, with the terms 'risk' and 'uncertainty' used interchangeably (eg: Lumby, 1984:108) with their designations conflated to mean the general "absence of certainty" (McKenna, 1986:9).

87 This was the title of his Nobel Memorial Lecture delivered in 1974 (Hayek, 1978:23).

Serious as they are, these difficulties are unfortunately only a part of the problem faced in the appraisal of technological risk. For the formal theoretical definitions of risk and uncertainty imply two further complementary conceptual categories (the right hand column in Figure 1). One might be termed a condition of 'ambiguity', under which the various possible outcomes do not admit discrete definitions (the top right quadrant of Figure 1) [88]. Where the degree to which the different outcomes are actually manifest can be expressed in numerical terms akin to the assignment of probabilities, then the techniques of 'fuzzy logic' may be applicable.

Of greater significance for present purposes, however, there is the condition that has been dubbed *ignorance* [89]. This is a state under which there exist neither grounds for the assignment of probabilities, *nor* even a basis for the definition of a comprehensive set of outcomes (the lower right hand quadrant in Figure 1). Such a situation may arise for instance, where analysis is defied by the sheer number of permutations generated by a variety of incommensurable performance criteria, each defining a scale of possible states [90]. Described variously as 'epistemological' or 'ontological' in character [91], or 'substantive' or 'procedural' in form [92], there exists a multitude of alternative typologies which seek to characterise the different detailed states and degrees of this condition of ignorance. It arises from many familiar sources, including incomplete knowledge, contradictory information, conceptual imprecision, divergent frames of reference and the intrinsic complexity or indeterminacy of many natural and social processes [93]. It emerges especially in complex and dynamic environments where agents may themselves influence (in indeterminate ways) supposedly exogenous 'events' [94] and where the very identification of particular courses of action can exert a reflexive influence on the appraisal of alternatives. Put at its simplest, ignorance is a reflection

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88 The author is grateful to David Fisk for a conversation concerning the status of fuzzy logic under this scheme. Where categories of 'outcomes' are conceived in terms of set theory, the assignment of 'fuzziness' in Box 2 rests on an analogy for members of outcome sets between 'probabilities of eventuation' and 'degrees of set membership', both of which are expressible as numerical weightings normalised to sum to unity. Cf: Klir and Folger, 1988; Dubois, et al, 1988; Zadeh and Kacprzyk, 1992; Kosko and Isaka, 1993 and Smith, 1994a, 1994b.

89 For various perspectives, cf: Shackle, 1968; Loasby, 1976; Collingridge, 1982; Ford, 1983; Smithson, 1989; Faber and Proops, 1994. The waters are rather muddied by the use of the term 'ignorance' in rather different contexts and with even more divergent implications, (cf especially: Shackle, 1968; Ford, 1983) and Dempster-Shafer theory (Yager, 1992).

90 As argued by Rosenberg (1996:340): "If uncertainty exists along more than one dimension, and the decision maker does not have information about the joint distribution of all the random variables, there is little reason to believe that a 'rational' decision is possible or that there will be a well-defined 'optimal' investment or adoption strategy".

91 See Winkler (1986) and other essays in Winterfeldt and Edwards, 1986. Also: Rosa, 1998.

92 Although discussed in relation to the term 'uncertainty', Dosi and Egidi's (1987) distinction applies also to what is here termed 'ignorance'.

93 There is an enormous number of different schemes for categorising the various forms and sources of incertitude. For useful reviews see especially: Smithson, 1989; Morgan, Henrion and Small, 1990; Funtowicz and Ravetz, 1990; Rowe, 1994; Faber and Proops, 1994.

94 Dosi and Egidi, 1987.

of the degree to which "we don't know what we don't know" [95]. It is an acknowledgement of the importance of the element of 'surprise' (whether positive or negative in nature) [96] - emerging not just from the actuality of unexpected events, but from their very possibility [97].

Such descriptions of the connotations of ignorance are, of course, a far more realistic approximation to the practical conditions pertaining in the regulation of technological 'risk' (in the broad sense) than are those underlying the formal concept probabilistic of 'risk' (in the strict sense). This is not to deny tat certain aspects of the appraisal of technological risks cannot usefully be modeled in probabilistic terms. The point is rather that exclusively probabilistic characterisations of technological incertitude are often in many crucial respects seriously *incomplete*. Indeed, it becomes clear that the conventional usage of the term 'risk' (in phrases such as the 'technological risk' at the heart of this report), is far broader and more complex than is the formal 'scientific' definition of the concept of 'risk' founded in probability theory. There is a serious danger that confusion over terminology may contribute to the mistaken application of inappropriate techniques to the regulatory appraisal of technologies under conditions of intractable uncertainty and ignorance.

The crucial point arising from this brief review of the theoretical foundations of risk assessment, then, is that the formal concept of 'ignorance' is founded just as rigorously in the theory of risk as is the concept of 'risk' itself. Indeed, the implication of a complementary concept of 'ignorance' is an inextricable consequence of the assumptions necessary in defining the concept of 'risk'. Although it has been observed that scientific culture is often characterised by a fear of admitting ignorance **[98]**, the formal concept itself is no less 'scientific' than is the probabilistic notion of risk. Indeed, what Hayek called the 'pretence at knowledge' displayed in the misplaced application of risk assessment under conditions of ignorance may actually be seen as running counter to the positivistic principles of science. In this sense, then, it is the precautionary acknowledgement of ignorance, rather than the uncritical pursuit of risk assessment, which can be seen to offer the most 'sound scientific' approach to the regulation of technological risk.

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[95] Reflecting the well worn aphorism attributed to Pliny to the effect that "the only certainty is that nothing is certain" (Pliny the Elder, 25-79 CE, *Historia Naturalis*, Book II, 7 – cited in Morgan and Henrion, 1990:*title page*). Ignorance reflects our uncertainty about our uncertainty (cf: Cyranski, 1986).

[96] Brooks, 1986. Perhaps because of the pejorative or pessimistic overtones of the term 'ignorance', there seems in some quarters to be a somewhat greater readiness to formulate the problem as one of 'surprise' (eg: Schneider, Turner and Garriga, 998). Perhaps for the same reason, numerous authors use adjectives such as 'partial' to qualify the term 'ignorance'. However, the present author believes that 'surprise' is a bad generic term for the condition itself, because it refers to the state of knowledge *after* the manifestation of developments rather than *before* and is therefore (unlike 'ignorance') inconsistent with the concepts of 'risk' and 'uncertainty'. Likewise, since - in the terms set out in Box 2 – the concept of ignorance is a precise complement for the concepts of 'risk', 'uncertainty' (and, perhaps, 'fuzziness') which are also available to describe aspects of real-life states of knowledge, it seems that the term 'ignorance' no more needs qualifiers than does the term 'risk'.

[97] Dosi and Egidi, 1987.

[98] Lindsay, 1995.

4.2 The Practical Importance of the Condition of Ignorance

There are numerous real-world examples of the practical importance of the concept of ignorance in the management of technological risk. The failure to anticipate the potential for depletion of stratospheric ozone by certain halogenated hydrocarbons, for instance, was not a matter of neglecting low probability events (under a 'risk' framework), nor even of the misassignment of probabilities under well-established causal models (involving 'strict uncertainty' as defined above) [99]. It was an example of the complete failure to identify even the very possibility of this outcome (and thus a manifestation of ignorance in the formal sense). Likewise, the chain of events which led to the development of the BSE crisis is better understood in terms of ignorance than as the manifestation of risk (or even uncertainty) in the formal sense [100].

Issues of ignorance arise in a number of ways with respect to energy and climate issues. It is intuitively quite plausible, for instance that a widespread shift to new energy sources (such as those involving renewable technologies) might lead to effects which is not only unknown in terms of their likelihoods, but whose very possibility is as yet unforeseen. The same is true, of course, in contemplating the long term effects of *continued* pursuit of *existing* energy technologies. Where attention is confined to a single unidimensional parameter such as temperature change, then the problem reduces to one of uncertainty – the possible 'outcomes' being fully characterised simply by intervals on a temperature scale. When attention extends to further dimensions of climate, or to consequent ecological, agricultural, economic, epidaemiological or social effects, the permutations of possible outcome parameters rises geometrically with the associated possible particular manifestations of climate change and are subject to ignorance in many ways [101].

As in other areas, energy risk assessment is confronted with questions of complexity, synergy and additivity in effects. It has long been recognised, for instance, that some forms of ecological impact have suffered from relative neglect because of the intricacy of the associated causal pathways [102] contributing to a tendency for health impacts to be generally over-represented in the appraisal literature compared to environmental burdens with no human impacts [103]. On the other hand, as was long argued to be the case with acid emissions, the causal complexity of certain health impacts may sometimes lead to their neglect in favour of ecological effects [104]. With respect to possible synergies, it cannot be assumed that the aggregate impact of a switch to large scale dependence on a wide range of novel renewable energy technologies will necessarily amount to the simple sum of its parts. The different effects of dispersed wind, wave, biomass and photovoltaic installations may alternatively be held to aggravate or to alleviate one another [105]. Such observations underscore the importance in energy risk assessment of the distinction often drawn between "direct" and "indirect" effects [106]. The latter may be very important. Yet where effects are the result of synergistic interactions between agents or activities, or which are in some other way causally complex, they are by their very nature subject to the predicament of ignorance.

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[99] Litfin, 1995.

[100] de Marchi 5151

[101] Schneider 5103

[102] Holdren, 1982 .

[103] IAEA et al, 1991b.

[104] Cohen and Pritchard (1980)

[105] Stirling, 1997.

[106] Eg: in IAEA, 1991.

A further issue which relates to the question of ignorance in the formal sense and which has long been recognised in the energy risk assessment literature concerns what Holdren has described as the confusion "between things that are countable and things that count" [107]. The effects associated with different options may not all be equally quantifiable. Damage to agricultural produce or other property may relatively uncontroversially be accounted for in monetary terms. Waste management problems may satisfactorily be expressed in terms of the appropriate mass or volume accumulations. However the same is not true of factors such as aesthetic appreciation of the landscape, or of attachments to the existence of unspoilt wilderness or sites of particular cultural importance. Even with health effects, serious difficulties are raised in attempting any one-dimensional comparison (in terms of mortality frequency) between the many divergent forms and contexts of human illness. Indeed it is often acknowledged that quantifiability and relative seriousness are often unrelated [108], and may even be inversely correlated [109]. When it is realised that the effects of different energy options may be quantified to differing degrees, the question is raised as to how to avoid an 'institutionalised ignorance' in the risk assessment field – artificially exaggerating the apparent performance of those options whose effects are least readily quantified [110].

Perhaps the best current examples of the practical importance of the concept of ignorance, however, lie in the fields of chemical and biotechnology regulation. Here, in its ideal form, the established probabilistic risk assessment paradigm involves the determination of precise dose-response relationships in relation to some linear or similarly straightforward model. In reality, the practice is rather different, with the routine use of 'uncertainty factors' to address contextual variability and inter- and intra-specific differences of sensitivity in the deriving of human safety standards from animal toxicology results [111]. These simple numerical multipliers are an implicit acknowledgement of at least some degree of ignorance in appraisal, in that they are included to represent *certain types* of factors which remain unaccounted for in analysis. However, the particular values taken by particular 'uncertainty factors' for particular agents in individual regulatory regimes (or advocated by different authorities), may vary by several orders of magnitude [112]. The possible implications for the regulation of the chemicals concerned can often be profound.

Even where dose-response relationships are held to be confidently determinable within the terms of the probabilistic paradigm, the regulatory utility of risk assessment may still remain problematic. One further source of potential difficulty in this regard are 'non-monotonicities', where intermediate concentrations are (under certain circumstances) found to be *more* hazardous than higher or lower concentrations. These can arise in considering the behaviour of a variety of different agents in complex environmental or biological systems. Such is reportedly presently suspected to be the case, for instance, with the compound bisphenol-A (used in the plastics industry) [113]. It has for many years been known to be a feature of the interactions between hydrocarbons, nitrogen oxides and ozone in urban smog [114]. Where dose-response relationships lie within the region of regulatory concern and are non-monotonic for the conditions expected in practice, then not only the theoretical foundations, but also the practical regulatory utility of risk assessment results themselves, is seriously compromised and complicated.

Unfortunately, however, the dominant uncertainties in chemical regulation go well beyond those over the form taken by the various probabilistic dose-response curves or simple numerical 'uncertainty factors'. For

[107] Holdren, 1982:38.

[108] Cohen and Pritchard, 1980.

[109] Holdren, 1982.

[110] cf: UNEP, 1985:190.

[111] Millstone, 1989

[112] Danish Board of Technology, 1996.

[113] ENDS 268, 5/97

[114] Brooks, 1986

instance, the potential endocrine disrupting properties of compounds such as phthalates which are now of strong regulatory concern lay until recently – even as a *category* of harm – effectively outside the conceptual framework of formal risk regulation [115]. Hormonal effects are still excluded from current animal toxicity test protocols within the EU [116]. A similar state of affairs may often apply with respect to the synergistic or additive effects of different compounds, either when contained in a particular effluent stream, or when subsequently brought into contact in the environment itself. The World Health Organisation has expressed concern over the potential importance of synergistic effects, but these are also not assessed under current regulatory appraisal in the EU [117]. Even simple additive effects are often excluded in the setting of safety standards – each substance being taken in isolation on a case by case basis [118].

Attempts to apply risk assessment to the regulatory appraisal of genetically modified crops also incur a vulnerability to a host of possible outcomes which are not only of unknown likelihood, but which may be entirely unforeseen. This predicament applies in particular with regard to current EC regulatory provisions under which a novel food or food ingredient is deemed to be 'equivalent' to its conventional counterpart unless established risk assessment techniques can show this not to be the case [119]. The incorporation of genetic material from brazil nuts into soybeans, for instance, has been documented to carry with it an allergenic property which was previously entirely absent from the soya products [120]. Yet, the mechanisms of allergenicity are acknowledged by the British Royal Society (among others) to be only poorly understood, thus rendering similar potential allergenicity problems "impossible to predict" [121]. The use in the production process for some genetically modified crops (like maize) of antibiotic resistant marker genes was, likewise, not initially a factor accounted for in the risk assessments conducted by the producer or certain national regulators [122] but has since been widely identified to hold the potential unacceptably to aggravate problems of antibiotic resistance in bacteria affecting human beings **[123]**. These illustrate the profound limitations to notions of 'equivalence' based simply on orthodox risk assessment.

Other initially unforeseen consequences of the genetic modification of crops are now becoming well documented. One example concerns the introduction of genes for herbicide tolerance. The original rationale for the engineering of tolerance in some genetically modified crops to sulfonylurea herbicides is based on the relatively low toxicity of these herbicides to humans. However, evidence is now emerging that, even at low concentrations, these chemicals may disrupt reproduction in non-target crops [124], with consequent potentially serious agronomic and ecological implications. In somewhat different vein, the use of genetic material from *Bacillus thuringiensis* (Bt) in herbicide-tolerant soybeans, corn, cotton and potatoes, confers an insecticidal property on the modified crops themselves, but also presents the possibility of inducing insect resistance to one of the very few pest control interventions permitted under organic and integrated

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[115] POST, 1997.

[116] Danish Board of Technology, 1996

[117] Danish Board of Technology, 1996

[118] Santillo et al, 1998.

[119] Article 8 of Regulation EC/258/97.

[120] Nordlee et al, 1996

[121] Royal Society, 1998:12

[122] de Marchi and Ravetz, 1998

[123] Royal Society, 1998.

[124] Krimsky, 1997:27

pest management strategies [125] Such effects not only defy probabilistic characterisation, but lie entirely outside the narrow frame of reference of conventional formal risk-based regulation.

Another potential source of ignorance in the risk assessment of genetically modified crops concerns not the possibility of unforeseen outcomes, but of unforeseen operational conditions or external circumstances. Risk assessment often requires the adoption of a wide variety of assumptions concerning the actual conditions of use. These can sometimes be somewhat simplistic or idealistic [126]. For instance, under the conditions actually experienced in the field, genes from transgenic herbicide-tolerant oilseed rape have been documented to transfer rapidly to wild relatives, thus threatening to generate a herbicide-resistant weed problem [127]. Likewise, the British Royal Society identifies the potentially harmful effects of the introduction into the food chain of genes transferred from crops engineered for the production of vaccines or pharmaceutical products [128]. As applies also in areas other than genetic modification, formal risk assessment can be highly dependent on assumptions concerning the strict adherence to good practice – in this case concerning issues such as the maintenance of isolation distances between crops. The increasing complexity, extent and competitiveness of global food markets raise serious questions over abilities to monitor and ensure complete compliance with the principles of good practice conventionally assumed in the risk assessment of genetically modified crops.

Taken together, these short examples drawn from the regulatory appraisal of energy technologies, chemicals and genetically modified crops illustrate that the formal condition of ignorance can have important practical repercussions. Not only is the concept of ignorance as scientifically well-founded as the concept of risk within the framework of probability theory, but it can hold direct and profound relevance for the management of technological risk. The problem is, that the many sophisticated techniques of risk assessment entirely fail – both in principle and in practice – to address the condition of ignorance in the appraisal of technology. In this sense, then, it must be concluded that the use of risk assessment cannot, in and of itself, be seen to amount either to a 'sound scientific' or an especially pragmatic approach to regulatory appraisal. The residual elements of incertitude which are not captured in risk assessment require additional – and complementary – provisions in appraisal. Far from being antagonistic, then, the adoption of a precautionary approach to the appraisal of technological risk is thus revealed as an essential feature of 'science based' regulation.

[125] Krimsky, 1997.

[126] Wynne, 1987.

[127] Mikkelson et al, 1996:31

[128] Royal Society, 1998

5 PROBLEMS IN REGULATORY APPRAISAL (2): INCOMMENSURABILITY

5.1 The Scientific Status of Incommensurability

As with ignorance, the second core problem in the regulatory appraisal of technological risk is also grounded in fundamental principles of 'sound science'. In this case, it is the problem of '*incommensurability*': the familiar difficulty in comparing apples and pears. Even where they are identical in their scope, different environmental appraisals or risk assessments may (implicitly or explicitly) embody different relative priorities on the various criteria under consideration. Here, the issues were explored more than forty years ago in great detail and with great rigour (in the terms of the rational utilitarian principles underlying risk assessment) by the economist Kenneth Arrow. The ensuing derivation of the notorious Arrow Impossibility Theorem helped earn its author a Nobel Prize and established some firm theoretical limits to what might be claimed on behalf of 'scientific' approaches to social appraisal such as risk and cost-benefit analysis.

Although the resulting analysis became very complex, Arrow's starting point was a relatively simple question. To what extent can problems of social choice (such as those addressed in the regulatory appraisal of technology) be held to conform to the basic rational principles which are assumed to apply (in fields such as economics and risk assessment) in the case of individual choice? Here, Arrow identified a set of five basic conditions which are conventionally held to be axiomatic properties of rational choice. First, that the ordering of preferences for each of a set of options should be the same irrespective of the way sub-sets of these options are grouped together (the "free triple condition"). Second, any option that is increasingly favoured by all individuals, should be increasingly favoured in the expression of social preference (termed "non-negative association"). Third, the introduction of new options, or the omission of old ones, should not alter the ordering of preferences for the other options (termed: "independence of irrelevant alternatives"). Fourth, if individuals are able to choose between any two options, then it should be possible to derive a social preference for one of these two options (the "non-imposition" condition). Fifth, under no conditions should social preference be determined by the preferences of any single individual (a "non-dictatorship" condition). In this work, as elsewhere, it is held to be axiomatic that rational preference orderings will be 'transitive', in the sense that if 'A' is preferred to 'B' and 'B' is preferred to 'C', then 'C' will not be preferred to 'A'.

These rather uncontroversial conditions apparently constitute a relatively permissive set of requirements on any social appraisal procedure. For instance, there is no condition imposing equity of weighting to the preferences of all individuals or constituencies in Arrow's list. Nevertheless, Arrow was able to show, using the formal language of axiomatic set theory, that the general derivation of a single social preference ordering (or aggregate social welfare function) over a number of social choice options will violate at least one of this minimal set of logical properties [129]. This seminal work has since been the subject of an entire literature in and of itself [130]. Yet, despite the complexities, the central insight remains intact [131]. In effect, Arrow showed that it is formally impossible to aggregate individual preferences in a plural democratic society in a rationally consistent fashion. No matter how much information is available, and no matter how much consultation and deliberation are involved, no purely analytical procedure can fulfil the role of a

129 Arrow, 1963, 1974.

130 These issues are discussed in more detail by Kelly (1978), MacKay (1980), Collingridge (1982), Bonner (1986) and Bezembinder (1989) with a convenient summary provided by Pearce and Nash (1981).

131 Sometimes being labeled "well known" in the critical literature (eg: Rayner and Cantor, 1987; Vatn and Bromley, 1994; Bohmann, 1996). See also: Lele and Norgaard, 1996).

democratic political process. In other words, in terms of the theoretical framework of rational choice theory underlying risk assessment, there can be no single uniquely "rational" way to resolve contradictory perspectives or conflicts of interest in the regulation of technological risk a plural society [132].

The implications of this (and related insights) for the practical business of the regulatory appraisal are clearly profound. The performance of a range of possible technological options (such as energy sources, chemical substitutes or alternative agricultural strategies) are usually characterisable under a number of disparate appraisal criteria. Depending on the context, these may involve consideration of financial, environmental, employment, regional development or other strategic political or economic factors. Even under a relatively narrow commercial perspective, decision-making typically trades-off considerations such as short run profits, long run competitive position, regulatory exposure, reputation management and labour relations.

From the point of view of the institutions charged with the regulation of technological risk, a wider range of different factors must be taken into account. Drawing on a broad body of literature concerned with the risk assessment of energy technologies, Figure 2 summarises some of the key dimensions in regulatory appraisal in this area. Likewise Figure 3 lists a variety of criteria advocated by different constituencies as factors in the regulatory appraisal of genetically modified crops in the UK. In each case, many individual criteria might themselves be disaggregated into a series of more finely-specified sub-issues. Whether choices are made in a public or a private capacity, the relevant appraisal criteria (and their constituent sub-issues) will often be *incommensurable*, in the sense that they cannot readily or unambiguously be aggregated under any single yardstick. It is possible to take different but equally reasonable views on the relative importance of the different decision criteria. The resulting judgements embodied in any individual risk assessment will thus necessarily be intrinsically subjective.

Of course, the problems of incommensurability apply not only to probabilistic, comparative and environmental risk assessment [133], but to the entire battery of analytical approaches employed in different contexts in the social appraisal of technologies, including decision and policy analysis [134], life cycle analysis and environmental impact assessment [135], multi-attribute utility theory and multi-criteria evaluation [136], orthodox and 'constructive' technology assessment [137], as well as the various forms of environmental cost-benefit and cost-effectiveness analysis [138]. Although each technique is distinct in its own way, what many of these approaches hold in common is a tendency to treat the broad notion of investment, technology and policy performance as an objectively determinate quantity, with the task of appraisal being simply to

132 Hogwood and Gunn, 1984. To the extent that they involve the compression of incommensurable values onto a single metric, analytical tools such as the Kaldor-Hicks compensation principle and the Paretian notions of welfare adopted in cost-benefit analysis do not resolve this problem.

133 Eg: Covello et al, 1985; Suter, 1991; Royal Society, 1992.

134 Eg: Collingridge, 1982; Winterfeldt and Edwards, 1986; Hogwood and Gunn, 1984.

135 Eg: Lee, 1989; Wathern, 1988; OECD, 1993; van den Berg, Dutilh, Huppes, 1995.

136 Eg: Keeney, Raiffa and Meyer, 1976; Janssen, 1994; Nijkamp, Rietveld and Voogd, 1990; Bogetoft and Pruzan, 1991.

137 Eg: articles in International Journal of Technology Management, 11(5/6), 1996; Rip, Misa and Schot, 1996.

138 Eg: Pearce and Nash, 1981; OECD, 1989; Pearce and Turner, 1990; Cropper and Oates, 1991.

identify the 'best' among a series of options [139]. To this extent, they share the objective of converting the fuzzy and controversial socio-political *problems* of investment appraisal, technology assessment and policy analysis into precisely defined and relatively tractable analytical *puzzles* [140]. In other words, they seek an 'analytical fix' for the politics of regulating technological risk. Although the basic difficulties and inconsistencies may be well known to the specialists, they tend to be neglected in the presentation of analysis for regulatory appraisal.

Building on earlier work in areas such as energy input/output analysis [141], the emerging discipline of life cycle analysis has made great strides in seeking to standardise the appropriate definition some of the different dimensions of appraisal (such as 'system boundaries') with respect to the technological options under appraisal in different instances **[142]**. However, it remains the case that there is still considerable scope for interpretation eve those factors which *are* subject to methodological standardisation. Most of the dimensions listed in Figures 2 and 3 are not. Most importantly, however, the point is that any tendency for convergence towards standardisation around a particular set of conventional framing assumptions may lead to greater degree of consistency among actual appraisals, but does not address the fact that the adoption of other, equally rational, standardising assumptions might lead to different notions of the relative importance of different options.

Here, the breadth and depth of the importance of the Arrow Impossibility become clear – not just in regulatory appraisal but in policy analysis more generally. The problem is not that it is difficult *in practice* to assign overall social priorities to the different considerations which inform technology, policy or investment choice in any given context. Rather, the message is that it is impossible *in principle* even meaningfully to *conceive* of a single 'objective' aggregated ordering of priorities. Such questions are intrinsically a matter of subjective value judgement. The aspirations (and tacit claims) made by risk assessment as an 'analytical fix' for the problems faced in regulatory appraisal are thus seen as violating fundamental scientific principles. The notion that there *must* exist a technology, policy or investment choice which is 'optimal' (or even in some sense unequivocally 'best') from the point of view of society as a whole, is fundamentally flawed. As in the case of ignorance, it is the more humble and circumspect approach of precaution which can claim greater consistency with the principles of 'sound science'.

[139] Although sometimes ambiguous on this point - especially where cultural theory approaches are applied (eg: Schwarz and Thompson, 1990, cf: critique in Stirling, 1998), constructive technology assessment is properly an exception to this generalisation (cf: Rip, Misa and Schot, 1996).

[140] The distinction is that of Thomas Kuhn (1970).

[141] Mortimer, 1991

[142] As embodied in ISO 14040 building on the work of the Society for Environmental Toxicology and Chemistry (SETAC).

Figure 2: some intrinsically subjective value judgements in the assessment of energy risks [143]

Severity: Do the options differ in the ratios of risks of death to risks of injury or disease which they pose? How much illness or how many serious injuries equate in severity with one death? (Eg: offshore wind and wave vs biomass).

Immediacy: Are the effects associated with different options equally immediate in their manifestation or do they differ in the degree of latency between the initial commitment of a burden and the eventual realisation of an effect? For instance, are some risks manifest as injuries and others as disease? (Eg: rooftop solar arrays vs nuclear power).

Gravity: Are the risks associated with some options dominated by low probabilities of large impacts, while those of other options are characterised predominantly as high probabilities of relatively low impacts? To what extent are impacts the result of single or repeated events? (Eg: nuclear vs coal).

Reversibility: Are the effects associated with different options all equally reversible after they have been committed? (Eg: nuclear and fossil fuels vs wind)

Spatial Distribution: Are the effects associated with different options identical in their spatial extents? Is it better that impacts of a given magnitude be geographically concentrated or dispersed? (Eg: wind vs fossil fuels).

Balance of Benefits and Burdens: To what extent is the social distribution of the environmental burdens caused by each option balanced by the distribution of associated benefits? (Eg: distributed vs centralised).

Fairness: To what extent do the distributions of burdens imposed by the different options act to alleviate or compound pre-existing patterns of privilege or social disadvantage? To what extent should exposure to other (unrelated) risk-inducing agents be taken into account in assessing the acceptability of incremental burdens? (Eg: urban waste-to-energy vs domestic PV).

Public or Worker Exposure: To what extent do different options impose different distributions of risks across workers and the general public? (Eg: offshore wind vs oil).

Intergenerational Equity: Do the effects associated with certain options present risks to future generations to a degree not associated with others? What is the appropriate discount rate, if any? (Eg: nuclear and fossil vs renewables).

Human or Non-human: Do the options differ in the degree to which their impacts affect the well-being of humans and non-human organisms? (Eg: biomass vs gas).

Voluntariness: Do the environmental effects of different options vary in the degree to which exposure may be considered to be ‘voluntary’ prior to the commitment of an impact? (Eg: do-it-yourself home insulation vs centralised coal).

Controllability: Once committed, are the impacts associated with different options all equally controllable from the point of view of the individuals or communities who stand to be affected? Do certain effects require efforts at control which are perceived to pose a threat to democratic institutions or processes? (Eg: nuclear vs wind).

Familiarity: Do the effects associated with different options differ in terms of the degree to they are familiar to individuals, communities and established social institutions? Do responses to the different effects involve equally disruptive changes to normal routines and attitudes? (Eg: nuclear vs biomass).

Trust: Do options differ in terms of the degree of trust enjoyed in the wider society by the institutions and communities charged with evaluating and managing their associated risks? Does the appraisal of certain options tend to be more a specialised undertaking than that of others? (Eg: nuclear vs biomass).

Quantifiability: Are the effects associated with different options all equally quantifiable? How has appraisal avoided a disproportionate emphasis on the more quantifiable aspects - and thus an overemphasis of the impacts of the associated options? (Eg: nuclear waste vs aesthetic landscape impacts).

Coherence: How coherent is the classificatory scheme adopted in any particular study with respect to the full range of environmental effects? Are there gaps or overlaps between the different classes of effect which are recognised for the purposes of analysis? (Eg: emissions, burdens, or effects).

Ignorance: How important is the element of surprise? Do some effects involve complex, novel or highly contingent mechanisms more than others? Are there are large discrepancies in the degree of established experience with particular options or effects? (Eg: genetically engineered biomass vs wind).

Trajectories: How long a historic data series is appropriate as a basis for the appraisal of current options? How robust are assumptions concerning the likely future behaviour of those at risk? Are different options on different ‘learning curves’ in terms of the potential for future improvements in performance? (Eg: radioactive waste, photovoltaics).

System Boundaries: How systematically does analysis address the resource chains and facility life cycles associated with the different options? How far back into the wider economy should analysis regress in assessing energy and material inputs? (Eg: material and energy inputs to renewable capital equipment, overseas uranium mining for nuclear).

[143] Discussed in more detail with references in Stirling (1997).

Articulation: How are the results of analysis to be articulated with wider considerations and the subsequent decision making process. At what point does the domain of analysis end and that of politics begin? (Eg: are results to be regarded as 'real', 'true' or 'full'?).

Figure 3: some criteria applicable to the regulatory appraisal of genetically modified crops [144]

ENVIRONMENT	Biodiversity	*eg: field boundary ecology, other environmental risks*
	Chemical use	*eg: reduction in use of existing herbicide sprays, benefits of contact herbicides versus soil acting residuals, longer term pollution of air and water*
	Genetic pollution	*eg: gene flow to other crops and native flora*
	Wildlife effects	*eg: Impact of enhanced weed control efficiency on wildlife, other practices affecting wildlife value of agricultural systems*
	Unexpected effects	*eg: potential for effects not foresee under this scheme*
	Visual	*eg: amenity impacts]*
	Aesthetics	*eg: feelings about environment*
HEALTH	Allergenicity	*eg: from food consumption*
	Toxicity	*eg: human or animal health*
	Nutrition	*eg: to consumers*
	Unexpected effects	*eg: unexpected interactions between ingredients, stability of genetic insert*
	Ability to manage	*eg: traceablility and ease of recall*
AGRICULTURE	Weed control	*eg: invasive volunteers and weedy relatives*
	Food supply stability	*eg: sustainability, tendency to monocultures, global food security*
	Agricultural practice	*eg: farmers' rights, choice and quality of life, land requirements*
ECONOMY	Consumer benefit	*eg: retail price*
	Producers benefit	*eg: shorter term costs, yield or longer term value added*
	Benefit to processor	*eg: profitability*
	Socio-economic impact	*eg: welfare of small farmers, substitutions for developing countries*
SOCIETY *pluralism*	Individual impacts	*eg: consumer choice, transparency, accessibility, participation,*
	Institutional impacts	*eg: concentration of power, institutional trust, regulatory complexity*
	Social needs	*eg: new opportunities, opportunity costs, misuse of science, employment, quality of life*
ETHICS	Fundamental principles	*eg: animal welfare, taking care of nature*
	Knowledge base	*eg: hubris about scientific knowledge*

[144] Resulting from a multi-criteria appraisal Mayer and Stirling (forthcoming).

5.2 Some Practical Implications of Incommensurability

A glance at Figures 2 and 3 is sufficient to illustrate the point that the different dimensions of the risks posed by energy or agricultural strategies are 'incommensurable' in the sense that they cannot readily or unambiguously be reduced to a single measure of performance. How important is severity compared to gravity in the appraisal of energy risks? What is the appropriate priority of price reductions compared to reduction in allergenicity risks in the appraisal of genetically modified organisms? The relative weightings attached by different constituencies in a plural society such as that of the EU to the different factors in appraisal are matters of fundamentally subjective value judgement. As was demonstrated from first principles by Arrow, differences of perspective are not amenable to resolution by means of rationalistic 'analytical fixes' such as those offered by the conventional techniques of risk assessment or cost-benefit analysis. Within a broad 'reasonable' range, for instance, no particular relative weighting on, say, human health compared to biodiversity can be claimed to be inherently more 'rational' (and thence 'scientific' or for that matter 'precautionary') than any other.

It is important to be clear that this problem of incommensurability is entirely distinct from the problem of ignorance discussed earlier. As has been shown, both incommensurability and ignorance are equally well-founded scientifically. They may also interact in certain ways, for instance in the incommensurability of different judgements over the exposure to ignorance or when the incommensurability of outcomes enhances the condition of ignorance. However, the two properties can also vary independently. Two different dimensions of performance may be incommensurable even where there is no uncertainty whatsoever – whether under a condition of risk or ignorance. For example, the problem of incommensurability applies equally to the certainty of a trade-off between one death and one thousand injuries as it does when the quantities are somehow uncertain. Likewise, the condition of ignorance may apply under a situation of perfect commensurability, such as when all measures of performance are held to be reducible to monetary value. An example here would be the appraisal of long term profitability in a firm engaged in the development of wind power or genetically modified oilseed rape which may satisfactorily be accounted for by shareholders in monetary terms and yet be subject to a host of unforeseen (and unforeseeable) eventualities of the kind experienced under the condition of ignorance.

Once this is accepted, then the question may reasonably be posed as to how the property of incommensurability impacts practically in risk assessment? Whether in the fields of energy, chemicals or genetic modification, the results of risk assessments conducted for regulatory purposes are often expressed with quite fine precision. Indeed, in energy sector risk assessments, human mortality and associated 'external cost' estimates are frequently presented to two [145], three [146] and even four [147] significant figures (equivalent to a precision of one part in ten thousand). The results of recent 'externality studies' in this field are often presented as discrete numerical values, with no range of variation acknowledged at all [148]. At most, the variability acknowledged in individual studies may amount to a difference of factor ten between high and low values [149].

However, when attention turns from individual studies to an entire body of literature as a whole, the picture changes quite radically, revealing the full magnitude of the impact both of ignorance and of incommensurability in appraisal. Figure 4 displays the values obtained over a number of years by industry

145 Eg: Hamilton, 1978; Inhaber, 1978, Fritzsche, 1989.

146 Eg: Comar and Sagan, 1976; Cohen and Pritchard, 1980; Holdren e al, 1980; UNEP, 1985; Voss et al, 1989; Ottinger et al 1990; IAEA et al, 1991.

147 Eg: Hohmeyer 1988; 1990.

148 Eg: Ottinger et al [1990]; Pearce et al [1992].

149 Eg: Hohmeyer, 1988, 1990, 1992.

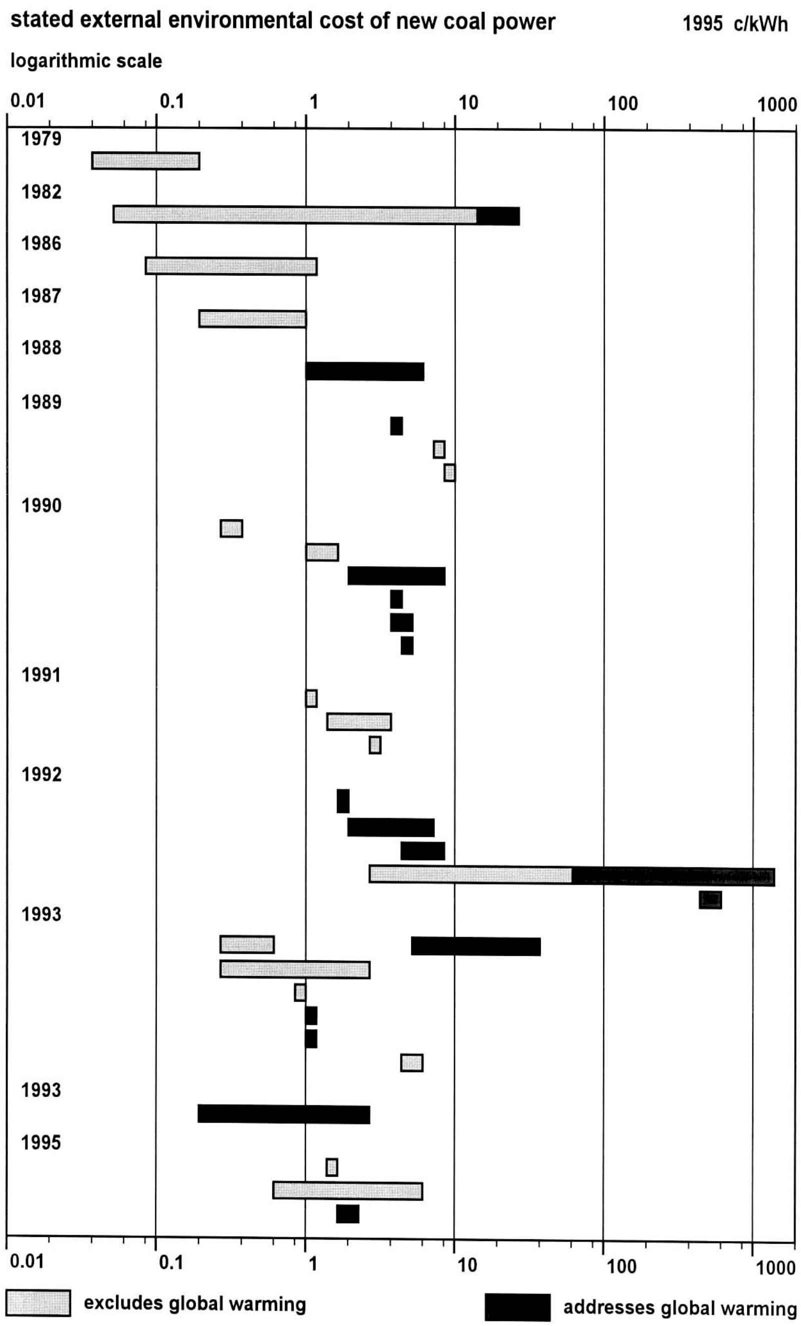
and government-sponsored studies in industrialised countries of the risks and environmental impacts associated with modern coal-fired electricity generating technologies (expressed as monetary 'external costs' in constant US currency terms) [150]. The uppermost values of the highest range approach twenty dollars per kilowatt-hour. The lowest values of the bottom range are less than four hundredths of a cent per kilowatt-hour [151]. The difference is more than four orders of magnitude – a factor of more than fifty thousand! There is no categorical trend evident over time, nor even a consistent relationship between the results of those studies which include and exclude crucial factors such as global warming [152].

[150] The results are expressed in US dollars at 1995 prices. They are, in the order displayed in Figure 4, those of: Ramsay, 1979; Shuman and Cavanagh, 1982; ECO Northwest, 1987; EPRI, 1987; Hohmeyer, 1988, Chernick and Caverhill, 1989; Shilberg, 1989; CEC, 1989; Friedrich et al, 1990; Koomey, 1990; Hohmeyer, 1990; Bernow and Marron, 1990; Ottinger et al, 1990; Bernow et al, 1990; Hagen et al, 1991; Koomey, 1991; Stocker et al, 1991; DTI, 1992; Hohmeyer, 1992; Cline, 1992; Ferguson, 1992; Hohmeyer et al, 1992; Externe, 1993; Friedrich et al, 1993; Eyre and Jones, 1993; Fankhauser, 1993; Pearce, 1993; Lazarus et al, 1993; Meyer et al, 1994; Eyre, 1995; Externe, 1995 and Tol, 1995.

[151] Where an individual study acknowledges variability or uncertainty by stating a range of values, this is represented in Figure 4 by a horizontal bar. One of the single most important dimensions of variability is addressed by showing the inclusion or exclusion of consideration of global warming effects in the shading of these bars.

[152] Values including and excluding attention to global warming overlap across an interval which is some two and a half orders of magnitude wide. Some of the lowest values obtained in the literature as a whole involve some consideration of global warming, while some of the highest overall values actually exclude this effect.

Figure 4: variability and uncertainty in assessments of the risks of energy technologies



Of course, in any discipline, different analysts will always employ different frames of reference, use different data, adopt different assumptions, and proceed by different methodological routes. Likewise, different approaches to risk assessment will relate to disparate regional and facility-specific circumstances. As a consequence, results generated by a set of appraisal studies will tend to spread over a range of values. However, when the range of variation of the results obtained for a single technology by a set of studies (sponsored by only one or two constituencies in a wider discourse) extends to more than four orders of magnitude, then it is difficult to explain the discrepancies simply in these terms. At the very least, it is clear that the accuracy of risk assessment does not match the precision with which individual authors express their results.

What emerges from more detailed review of the methodologies and framing assumptions employed in the different risk assessments reviewed in Figure 4 is that it is subjective judgements over incommensurable factors such as those listed in Figure 2 which are responsible for the variability in the results. Different studies vary radically in their scope – addressing different factors to differing extents, amounting effectively to the placing of different emphasis on incommensurable criteria such as atmospheric pollution, accident risks or aesthetic impacts. Likewise, different studies impose different assumptions over 'system boundaries', adopt different conventions over the trajectories of different technologies, use historic or projective data to different extents and employ different discount rates in accounting for future effects. Even within a section of the literature generated by government and industry bodies, then, divergent (and equally reasonable) judgements over incommensurable factors in appraisal can lead to enormous differences in the results obtained by risk assessment.

Of course, the confusion evident in the picture presented by risk assessment for an individual technology (in this case modern coal power) is compounded when attention turns to a comparison of the results obtained for a range of different technologies. Based on the same survey of government and industry risk assessments of electricity supply options, Figure 5 displays the externality values derived in the literature as a whole for eight key options. Again, the picture is dominated by enormous variability. Indeed, the lowest values obtained for the worst ranking option (coal) are lower than the highest values obtained for the apparently best ranking options (wind). Since individual studies show results at the high end of the overall range for some options but lower in the distributions for others, the overall picture would accommodate any conceivable ranking order for these eight options.

The Energy Sector from which this example has been drawn constitutes one of the longest established, most methodologically mature and most intensively researched areas for the application of regulatory risk assessment. The findings of the present rather wide-ranging survey are broadly supported by earlier reviews of smaller and more detailed areas of this literature [153]. The enormous variability in the values taken by uncertainty factors and other parameters in chemicals risk assessment points to a similar picture in that field [154]. Indeed, even in the comparatively recently developed field of genetic modification as-yet unpublished research involving the present author documents the radically different ranking orders for different agricultural strategies which can be obtained by conducting appraisal according to the framing assumptions and priorities of different constituencies [155]. Taken together, the implications are rather negative for the practical applicability and utility of risk assessment in the regulatory appraisal of technological options. One of the most basic tasks in risk assessment and environmental appraisal is to achieve some notion of the overall ranking of different options under different assumptions. Since many of the incommensurable dimensions of variability discussed here (and shown in Figure 2) typically remain implicit in risk assessment, serious questions must be raised over whether the associated results are of any practical policy use at all.

As was the case in the discussion of the problem of ignorance in appraisal, then, it can be concluded that concern over the problem of incommensurability is at the same time scientifically very well founded and of profound practical importance in the regulatory appraisal of technological risk. Again, the disciplines of

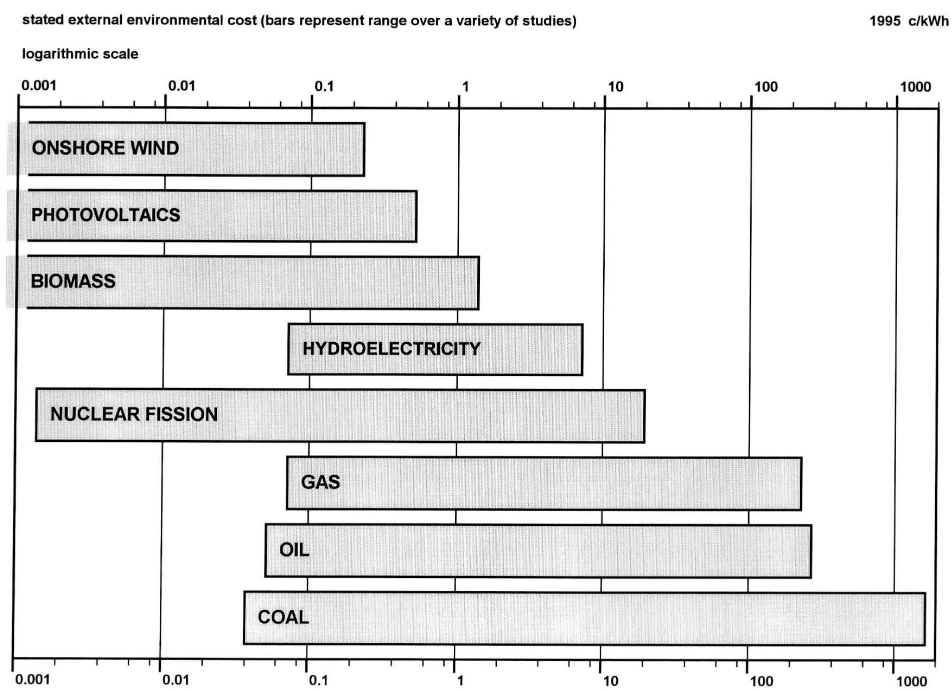
[153] Eg: Comar and Sagan, 1976; Holdren et al, 1980; Ferguson, 1981; Fritzsche, 1989.

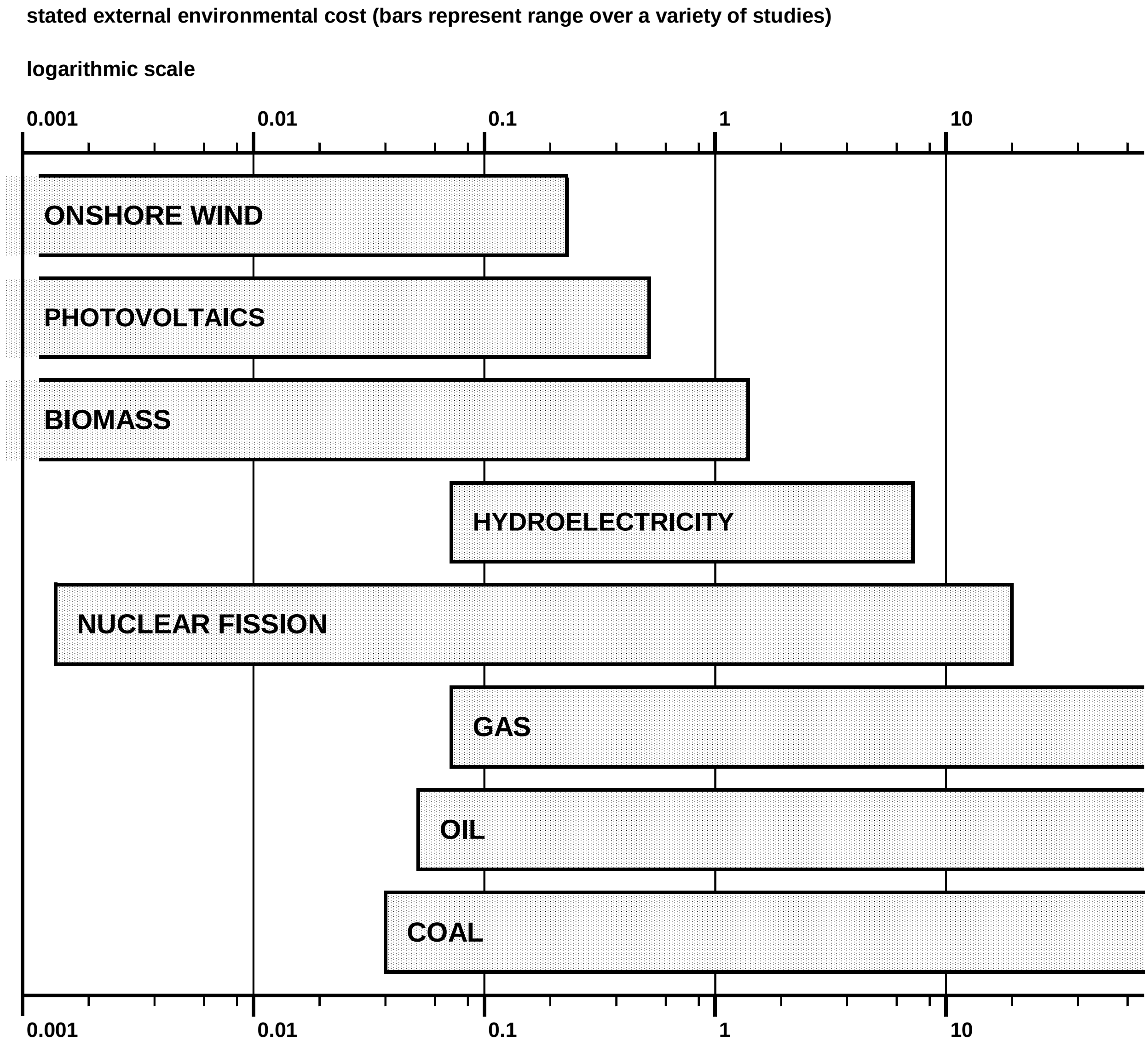
[154] Danish Board of Technology, 1996.

[155] Mayer and Stirling, forthcoming.

scientific rigour and precaution on this question point in the same direction. Where there exist no grounds to discriminate between the 'rationality' of contending value judgements and framing assumptions in appraisal, both the imperatives of precaution and scientific rigour require in common that equal and systematic attention be given to a broad range of representative and politically sustainable value judgements. The alternative – the adoption of a single circumscribed (possibly idiosyncratic) subjective position and its concealment behind ostensibly precise numerical risk assessment results – offers an alternative that is no more 'scientific' than it is 'precautionary'.

Figure 5: ambiguity of ordering in assessments of the risks of energy technologies




stated external environmental cost (bars represent range over a variety of studies)
logarithmic scale
0.001
0.01
0.1
1
10
ONSHORE WIND
PHOTOVOLTAICS
BIOMASS
HYDROELECTRICITY
NUCLEAR FISSION
GAS
OIL
COAL
0.001
0.01
0.1
1
10

6 SCIENCE AND PRECAUTION IN APPRAISAL: SOME PRACTICAL LESSONS

6.1 Introduction

The preceding sections of this interim report have established that recognition of the importance of ignorance and incommensurability in appraisal is as much a matter of 'sound science' as it is of 'precaution'. Focusing especially on examples drawn from the regulatory appraisal of energy technologies, chemicals and genetically modified crops, it has also been demonstrated that these fundamental theoretical concepts are of profound practical importance in the management of technological risk.

The purpose of the final part of this paper is to explore in a constructive fashion and in very general terms some of the main implications of these problems for the practical business of regulatory appraisal in areas such as energy technologies, chemicals and genetic modification. Rather than seeking to compound what has been argued to be an unproductive dichotomy between 'precaution' and 'science', attention will focus here on measures which are justified equally on the grounds both of 'precaution' *and* 'science-based regulation'. The discussion will necessarily be brief on each point and will focus on practical operational measures.

6.2 Broaden the Scope of Regulatory Appraisal

The first implication is that much conventional regulatory appraisal remains highly circumscribed in scope. There is a tendency for formal appraisal procedures to focus only on a small sub-set of the totality of issues which are of concern in the wider debate. This may be because the selected issues are more readily quantifiable, because they are more amenable to measurement under an individual favoured metric (such as human mortality or monetary value) or because of the artificial divisions of responsibility between different regulatory bodies. Whatever the reason, the effect is often unduly to limit the basis for regulatory decision making and to render inconsistent appraisals conducted on the basis of different patterns of restrictions [156].

Existing regulatory risk assessment is widely regarded to be unduly restricted, both in the areas of energy technologies and genetically modified crops [157]. Even on specific issues such as the environmental release of genetically modified crops, interpretations at national level of EC guidance is presently highly variable and inconsistent [158]. At present, for instance, only certain member states make efforts to include some account of complex and indirect effects in the regulatory appraisal of genetically modified crops [159]. A

[156] Stirling documents this for the energy sector (1997) von Schomberg (1998) documents the lack of harmony in framing of risk assessment under EC, 1990.

[157] Stirling, 1999 forthcoming; the scope of NRC and GMO workshop risk characterisation quotes. RS endorse 1994 Consensus Conference in calling for broadening of scope of regulatory appraisal on GMOs (5150:5-6).

[158] Von Schomberg, 1998.

[159] Von Schomberg, 1998.

further particular issue in this regard is highlighted by public interests groups [160] and industry alike [161] and concerns the exclusion from the scope of present regulatory risk assessment of some account of the magnitude of the wider public *benefits* which might be offset against any adverse effects. In the field of genetically modified crops, again, both the present EC regulations [162] and their proposed revision [163] exclude systematic account of benefits. As is increasingly called for by citizen consultations [164] and consumer [165], commercial [166] and scientific [167] organisations alike, the obvious response to this problem (both from a precautionary and a scientific point of view) is to significantly broaden the scope of the routine regulatory appraisal of technologies like genetically modified crops. All else being equal, the more complete the scope adopted in appraisal, the more 'precautionary' and 'scientifically sound' the associated regulatory decisions.

6.3 Acknowledge Intrinsic Subjectivity in Framing Assumptions

The preceding discussion in this interim report of the scientific status and practical importance of ignorance and incommensurability in regulatory appraisal underscores that many of the assumptions adopted in the framing of analysis (whether by risk assessment or some other technique) are exogenous to the analysis itself and to a large extent intrinsically subjective in nature. What may or may not appear to be an appropriate way of framing an individual appraisal will typically vary from perspective to perspective and from case to case. For instance, set against concerns over the possible carcinogenic potential of certain GM characteristics or on the part of associated broad-spectrum pesticides, there might also be concern over the carcinogenic properties of mycotoxins which may be held under some perspectives to be likely to be more prevalent in organically-cultivated foodstuffs. Here again, both a precautionary and a scientifically rigorous approach would hold in common the need openly to acknowledge the intrinsic subjectivity and context dependency of such framing assumptions and the associated volatility in the results which might be obtained in appraisal.

6.4 Maintain Humility in the Face of Ignorance

One of the most important practical conclusions that must be drawn over the operationalising of 'precautionary' and 'science based' regulation must be the necessity for humility over uncertainties in the appraisal of technological risk. Although the condition of ignorance is as scientifically well-founded as is

160 Genewatch, 1998

161 Novartis, 1998:372

162 EC, 1990

163 EC, 1998

164 1994 consensus conference, citizen foresight.

165 Hamstra, 1995

166 'Confronting Risk: report of a workshop run by Consumers Association, Unilever and Sainsbury's', London, 1998

167 Royal Society, 1998:5-6

that of risk, it is in its implications and by its very nature, indeterminate, context-dependent and open ended. No matter how well-informed, judgements concerning the extent to which "we don't know what we don't know" are – as with other framing assumptions – intrinsically subjective and value laden. Here again, then, both a scientific and a precautionary approach urge the adoption of greater humility concerning the applicability and robustness of the orthodox techniques of probability theory, risk assessment and even scenario analysis and the results which they yield in any given exercise in regulatory appraisal.

But what does this mean in practice? Many different strategies have been proposed in response to this dilemma. Humility over ignorance must certainly necessarily require procedures for ensuring the allowance of a 'margin of error' in appraisal [168]. Rather than elaborate stochastic modeling, appraisal might focus on deterministic 'sensitivity envelopes' derived through propagation of 'worst case' parameter and variable values [169]. This might be associated with implementation of a 'minimax' decision criterion, recognising an imperative to minimise worst case outcomes [170]. Beyond this, the appraisal of technological risks might include systematic 'ignorance audits' (based on various taxonomies for the forms and sources of ignorance) [171]. One sophisticated approach on these lines is the 'NUSAP' scheme proposed by Funtowicz and Ravetz, which sets out to address a range of divergent factors associated with incertitude, including the 'pedigree' (or epistemological status) of the theoretical framework within which the results have been derived [172]. Through use of such techniques, different risks can be treated differently in regulatory appraisal, depending on their judged susceptibility to ignorance. This is the case, for instance, in the classificatory scheme proposed as part of the present project by Renn and Klinke [173].

However, all such approaches remain subject to the concern that they rely on an ability to foresee the broad character (if not the fine detail) of the uncertainties faced in appraisal. Though useful, such approaches fall to some extent short of the full scope of ignorance as a condition under which "we don't know what we don't know". Those options which are apparently favoured in any 'ignorance audit' may yet turn out to incur adverse effects of a kind which are unforeseen even in the audit itself. In this regard, it might be that attention is also productively directed at the general system-level properties of the options themselves, such as the deliberate pursuit of diversity, flexibility, resilience and reversibility in the choice of energy, chemical and biotechnology strategies. These latter issues are discussed later in this report [174]. For the moment, the point is simply that, just as it must be acknowledged to be no less scientifically well-founded than the condition of risk, so the condition of ignorance displays no shortage of practical decision-making consequences.

6.5 Complement Analysis with Inclusive Deliberation

The regulation of technological risk in modern plural industrial societies such as those of the EU member states is beset with divergent, perceptions, interests and value judgements. If it is accepted that principles both of scientific rigour and of precaution require acknowledgement of the validity of ignorance and

[168] Jordan and O'Riordan, 1998.

[169] Gray and Bewers, 1996.

[170] Perrings, 1991.

[171] Dovers and Handmer, 1992.

[172] Eg: Funtowicz and Ravetz, 1989, 1991, 1992.

[173] Renn and Klinke, 1998.

[174] Sections 6.9 and 6.10.

divergent framing assumptions in appraisal, then the question is raised as to how such intrinsically subjective factors can be taken into account in a systematic, robust and legitimate fashion. How can regulatory decision making validate the particular subjective assumptions over option definitions, framing assumptions and priorities embodied in any given analytical exercise in regulatory appraisal? The answer is surely that the use of the 'best available science' in risk assessment must be complemented by the use of 'the best available procedures' for the interpretation of that science in relation to the multitude of perspectives typically brought to bear by different stakeholders on any technological risk issue.

Of course, principles of equity, democratic legitimacy and even political expediency and trust are all often taken to point to the need for regulatory appraisal to be as socially inclusive as possible [175]. Such factors are often held to present good 'normative', 'procedural' and 'instrumental' rationales for public participation. In other words, participatory deliberation might be seen alternatively as 'morally right' for its own sake in a democracy (a 'normative' rationale); providing for better decisions from the point of view of society as a whole (a 'substantive' rationale) and helping to ease the inconvenience and inefficiency of conflict over technological decisions (an 'instrumental' rationale)[176]. What is conventionally less well recognised, however, is that the full engagement of all interested and affected parties in appraisal is also a matter of *scientific rigour* in the narrowest of technical terms [177]. For, without the empirical validity conferred by an inclusive deliberative process, what can be the status of any particular set of options, framing assumptions and priorities adopted in any individual risk assessment? Whilst the scientific and technical information employed within any particular framework can be justified (within certain bounds) in terms of their scientific veracity, the same is not true for the crucial subjective assumptions which are exogenous to appraisal. Here justification can only be made by appeal to the acceptability of the associated sets of interests and values. Inclusive public deliberation is thus highlighted as a necessary part of any 'sound scientific' approach to the regulatory appraisal of technological systems such as those engaged in food and energy production.

In contemplating this dependence of rigorous analytical appraisal on inclusive public deliberation, the reciprocal relationship also emerges as a point of some importance. A notable phenomenon in many EU member states over recent years has been the emergence and increasing importance of 'deliberative institutions' such as 'consensus conferences', 'citizen's juries', 'planning cells' and 'focus groups' [178]. In certain member states (such as Denmark) such institutions already enjoy statutory status and a formal role in the conduct of appraisal for the informing of regulation. In some states (such as the UK, Italy and France) they are still at the experimental stage whilst in others (such as Germany and the Netherlands) the position is somewhat intermediate [179]. Throughout the EU (and industrialised countries more generally), issues such as genetic modification and technology choice for food and energy production are among the principal topics addressed by such approaches [180]. Just as orthodox risk or cost-benefit analysis face serious questions over the treatment of qualitative issues and divergent framing assumptions and values, so too do the new deliberative institutions often face challenges of competence, legitimacy and transparency. It therefore seems evident that there exist strong potential synergies between the new deliberative institutions and the comprehensive, pluralistic and open-ended approach to analytical appraisal for regulation of the kind that is prompted by precautionary and scientific imperatives alike.

[175] Eg: Fiorino, 1989; NRC, 1996.

[176] Fiorino, 1990.

[177] Stirling, 1998.

[178] Renn et al, 1996.

[179] Durant and Joss, 1995.

[180] Renn et al 1996; Durant and Joss, 1995

6.6 Conduct Comparative rather than Absolute Appraisal

The regulatory framework for the governance of new technologies (such as genetically modified organisms or renewable energy) tends to be based on the application of absolute standards of tolerability or acceptability, with risk assessment or environmental appraisal conducted in relation to individual options on a case-by-case basis in order to establish the degree to which such standards have been met. Individual applications to install an array of wind turbines, for instance, are typically assessed in isolation, rather than in relation to alternative siting possibilities for renewable or non-renewable generating plant in a particular area [181]. The same is typically true of larger scale electricity generating plant, where siting issues are usually approached on a case by case basis of a kind which tends to provoke strong 'not in my back yard' reactions [182]. A similar picture pertains in the regulation of genetically modified crops. The cultivation of each individual genetically modified crop is typically assessed in it's own terms, rather than in explicit comparison with alternative GM crops or agricultural strategies such as conventional intensive cultivation, integrated pest management or organic production [183]. Such an approach not only fails to take into account the relative performance of different options, but can easily lead to the neglect of cumulative effects which, while of relatively low significance in each individual case, might aggregate to present risks of some importance.

The assertion of absolute minimum environmental performance standards and their continued progressive revision in the light of changing expectations or knowledge is a central aspect both of the 'scientific' and of 'precautionary' approaches. However, within such a framework, the flexibility and creativity fostered by comparative approaches to regulatory appraisal is also increasingly coming to be recognised as an important element in environment policy. Such an approach was enshrined in EC law with the adoption of the Biocides Directive. It is reflected in the increasingly concrete implementation of concepts such as Best Available Technique (as embodied in the 1996 EC Directive on Integrated Pollution Prevention and Control building on earlier national practice [184]). Here, of course, a crucial issue surrounds the breadth of scope adopted in the definition of what constitutes a 'technique' with respect to any given purpose. The business of defining the contending options which are subject to comparative appraisal [185] will be predicated on the characterising and partitioning of operational *functions*. For instance, should BAT-style concepts in the field of renewable energy be defined at the level of an individual plant, at the level of a generic technology (such as wind, small hydro, biomass or solar power) or cross-cutting radically different electricity generating (or even demand side) technologies? Likewise, should a BAT-style approach to the regulation of GM crops be introduced at the level of particular genetically modified products or include more disparate alternative cultivation strategies? All else being equal, the broader the comparative framework employed and the more thorough and inclusive the deliberative approach undertaken in framing it, the more 'precautionary' and 'scientifically sound' (at least in terms of completeness) the appraisal process.

6.7 Harness the Potential of Multi-Criteria Techniques

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[181] Mitchell, 1998.

[182] See, for instance, articles in the special issue of the journal *Risk, Health, Safety and Environment*, **7**, 2, Spring 96.

[183] EC, 1990.

[184] Such as BATNEEC, BPEO and BPM in the UK.

[185] This task of co-ordinating the process of formulating BAT Reference Documents under the 1996 IPPC Directive, for instance, is assigned to the EC JRC IPTS in Seville.

The cumulative impression given by the discussion thus far may be rather daunting. The argument (made on the grounds both of 'precaution' and 'scientific rigour') for analysis to take account of a wide range of options, acknowledging subjectivity and variability in the choice, framing and prioritisation of appraisal criteria and recognising the intractabilities of strict uncertainty and ignorance may seem, on the face of it, to place some very demanding requirements on the process of regulatory appraisal. However, at one level, the addressing of these demands need not be taken to imply the rejection of orthodox quantitative techniques. In the disciplines of physics and engineering, for instance, a multiplicity of incommensurable properties are routinely characterised by means of matrix analysis. In physical terms, for instance, it would be meaningless to seek to combine in a single number the temperature, colour and mass of an object. In just the same way, the adoption of a 'scientific' approach need not be taken to imply the conflation of incommensurable properties in appraisal. Instead, each different dimension can be treated separately, with final judgements over relationships and trade-offs between criteria left to a separate deliberative process, rather embedded in the analysis itself. The various techniques of multi-criteria evaluation are now quite mature and have been developed over a number of decades precisely in order to allow the systematic manipulation, articulation and interpretation of performance attributes characterised in vector (rather than scalar) form [186].

Though not required (or even routinely applied) in statutory analysis for regulation, multi-criteria techniques are quite readily applicable (and, indeed, frequently applied outside formal procedures) to the challenges of option appraisal in fields such as agricultural and energy strategy. In addition to the matrix structure, they have the further merit that they are not dependent on the universal application of a particular quantitative metric (such as mortality or monetary value). The biodiversity risks presented both by renewable energy and by GM crops, for instance, are poorly characterisable either by monetary values or by mortality frequencies. Multi-criteria approaches allow each individual aspect of performance to be appraised under whatever seems the most appropriate yardstick. Such techniques thereby help to diminish the confusion "between things that are countable and things that count" which is characteristic of much orthodox quantitative appraisal. Where they stop short of prescribing a single numerical value for 'risk' (or a single definitive ordering of options) such approaches avoid falling foul of the Arrow Impossibility discussed above. To this extent, they may be seen both as more 'scientifically rigorous' and as more precautionary than are analytical approaches to regulatory appraisal such as orthodox risk assessment.

6.8 Express Analytical Results Using Sensitivity Analysis

A similar but quite distinct point relates to the expression of analytical results in the regulatory appraisal of technological risk. It has been shown in this interim report that – in a variety of areas – risk assessment results are often presented with a very fine degree of numerical precision [187]. Such a style conveys the impression of great accuracy, and distracts attention from the crucial question of the *sensitivity* of final results to changes in starting assumptions. This problem is particularly acute, where the values obtained – and even the ordering of different options – are quite volatile under the perspectives in appraisal associated with different social constituencies and economic interests. A practical and well-established way of dealing with such a problem lies in 'sensitivity analysis' – a technique involving the explicit linking of alternative framing assumptions with the results which they yield. Rather than being expressed as discrete scalar numbers, then, risk assessment results might be expressed as ranges of values, with the ends of the ranges

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[186] Eg: Keeney et al, 1976; Bell et al, 1977; Starr and Zeleny, 1977; Friend and Jessop, 1977; Rivett, 1980 Fischoff et al, 1980; Keeney, 1980; Pinkus and Dixson, 1981; Collingridge, 1982; Edwards and Newman, 1982; Voogd, 1983; Chankong and Haimes, 1983; Covello, et al, 1985; Arrow and Raynaud, 1986; Winterfeldt & Edwards, 1986; Saaty, 1988; Vlek and Cvetkovitch, 1989a; Nijkamp et al, 1990; Bana e Costa, 1990; Borcherding et al, 1990; Bogetoft and Pruzan, 1991; Clemen, 1991; Janssen, 1994.

[187] Section 5.2.

reflecting extremities in the framing assumptions associated with different stakeholders in the appraisal process.

It is interesting to reflect, in this regard, that (in fields such as engineering) the properties of even relatively simple deterministic systems such as bridges and buildings are routinely characterised using 'sensitivity analysis'. This presents a curious contrast with established practice in much risk assessment and environmental appraisal (which might reasonably be thought intrinsically more variable, complex, dynamic and indeterminate). The systematic 'mapping' of sensitivities (such as those reflecting context dependency, irreconcilable values, divergent option definitions and inconsistent framing assumptions, as well as varying conceptions of uncertainty and ignorance) offers a way of presenting the complexities of technology appraisal in a relatively clear and robust fashion. This is particularly the case where multi-criteria techniques are employed to address the different incommensurable dimensions of appraisal a part of a wider inclusive and deliberative process.

Here, it has to be admitted that multi-criteria approaches have – just like risk assessment or cost-benefit analysis - often been employed in the past without due attention to sensitivities [188]. Indeed, scalar notions of 'multi-criteria utility' are no less problematic as quantitative representations of complex indeterminate systems like energy or food production than are discrete numerical values for 'risk' or 'cost'. The point here is that it is the *combination* of inclusive participatory deliberation, systematic multi-criteria evaluation and comprehensive sensitivity analysis which offer a potentially productive synthesis which is more than the sum of the parts. However, it remains the case that, whether employed with multi-criteria, risk or cost-benefit analysis, the systematic mapping of sensitivities in its own right offers a way of addressing divergent perspectives in appraisal which is at the same time both scientifically rigorous and precautionary in character.

6.9 Maximise Transparency and Simplicity

The principle of Occam's Razor is a well established theme in scientific culture. Likewise, with respect to the adoption of a precautionary approach to appraisal, it might well be argued that (all else being equal) the more complex the appraisal technique employed, the more vulnerable is the process to oversight, error or manipulation. Either way, it is certainly the case that (on average) the more complex the analytical procedure, the more protracted and expensive the associated appraisal process is likely to be. Of course, the nature, complexity and breadth of the evaluative issues associated with technologies such as genetic modification or renewable energy (and the environmental and social systems in which they are embedded) require a certain minimal level of complexity in appraisal. Likewise, there is a sense in which the need for completeness of scope and comparability across different dimensions also militate against simplicity. Subject to these constraints, however, it seems clear that relative simplicity is a valuable feature in any appraisal methodology. The dependence of appraisal on elaborate mathematical models with many embedded parameters (especially those with stochastic variables) might (in these respect at least) be treated with some caution both from the point of view of precaution and of rigour.

A separate property, which is in many respects related to simplicity, is transparency. However, transparency refers not just to the structure and dynamics of an appraisal process, but also to the effectiveness with which this is represented and communicated to the outside world. Here, particular demands are placed by the need for effective provision for error correction and extended peer review. Transparency also serves a valuable function in contributing to the degree of public confidence and trust invested in an appraisal process as a whole. It is an essential ingredient in achieving the constructive synergy between quantitative analysis and inclusive deliberation which has already been discussed above. All else being equal, then, the greater the number of 'variables' and 'parameters' which remain unexplored (or even undeclared) in appraisal, the less transparent will be the outcome. In this way, complexity and

[188] cf: Stirling, 1996 for an example in this regard.

transparency in regulatory appraisal may therefore sometimes be regarded as being in tension. Although the type of systematic and comprehensive sensitivity testing discussed above might in some respects be seen to add to the complexity of an appraisal process, it also adds significantly to the transparency. Likewise, there is a tendency under some approaches for multi-criteria techniques to be extremely complicated – becoming dependent on elaborate, opaque and sometimes- counterintuitive computer modeling. The imperatives of scientific rigour and precaution alike demand the striking of a judicious balance between the degree of fidelity achieved in the treatment of the complexities and scope of the real world of risk, and the complexity and transparency of analysis as part of a wider process of regulatory appraisal.

6.10 Focus on Portfolios rather than Individual Options

It has already been noted that much of the activity in the regulatory appraisal of technological risks is aimed at establishing the 'tolerability' or 'acceptability' of an *individual* proposed investment, technology or policy against some absolute metric (such as mortality, morbidity or monetary value). However, even on those occasions where analysis extends to the comparative appraisal of a *range* of contending options, orthodox approaches to risk and environmental impact assessment still typically tend to be aimed at the identification of the *individual* option whose performance is rated highest under the metric in question. This is held to correspond with the identification of the single relatively 'best' choice from the point of view of society as a whole. In this sense, current comparative appraisal might generally be seen as a 'first past the post' approach – the 'picking of winners' in the regulation of technological choices.

An important conclusion drawn earlier in this interim report is that the notion of an objective 'best' choice from the point of view of society as a whole is, in the most fundamental of scientific terms, highly problematic. Nevertheless, in contemplating the intractabilities of ignorance and Arrow's Impossibility, it is quite remarkable that there exists one common-sense strategic response which stands out beyond all others and yet which is often neglected: "don't put all your eggs in one basket!". Instead of aspiring (let alone claiming) vainly to identify individual 'optimal' or 'best' choices from the point of view of society as a whole, might we not think instead in terms of the construction of *portfolios* of choices? The pursuit in parallel of a diverse portfolio of what are judged t be the better-performing options may at the same time accommodate divergent value judgements *and* help to hedge against ignorance in appraisal. Although itself a challenging task, the characterisation of diversity amongst a series of contending technological options presents a potentially far more tractable problem than the definitive characterisation of all possible future states of the world and the objective definition of an aggregate social welfare function across all available options. Indeed, where diversity is precisely characterised (as, for instance, in the field of ecology) it is even possible to derive quite robust numerical indices.

Agricultural and energy strategies alike are already characterised by a plurality of contending options pursued in parallel. In such fields, as in areas such as transport, health care and information technology, variations of circumstance from context to context (and market to market) are, in any case, responsible for yielding a *de facto* diversity in existing technological portfolios. In this way, there is no reason in principle why the diversification of options in the face of ignorance and pluralism might not be handled as readily as any other dimension of the risk assessment problem. Here, however, those options which are held to militate *against* diversity in some respect might be regarded particularly cautiously [189]. All-important trade-offs between diversity, cost and the various dimensions of risk may all equally be treated by 'sensitivity analysis' of the kind that has already been discussed. The crucial point here, is that such diversity might – up to a point and to a degree depending on the aversion to ignorance and the desire to accommodate plural perspectives – be taken as a deliberate regulatory strategy which conforms alike to the disciplines of 'precaution' and 'scientific rigour'.

[189] As has already been discussed above (in Section 4.2), genetically modified crops containing Bt toxins are held in many quarters to present particular risks to the continued integrity of organic farming techniques (eg: Royal Society, 1998).

6.11 Take Account of Qualitative Strategic Factors

Recognition of the potential significance of the attribute of diversity in the implementation of precautionary strategies in the regulation of technology may be seen to raise questions over the potential merits of other dynamic system properties in technological portfolios such those in the agricultural and energy sectors. Aside from the more orthodox parameters in risk and environmental appraisal (such as toxicity, persistence and the distribution of various emissions and waste arisings), a host of generic characteristics on the part of the technological options themselves may be regarded as factors worthy of some attention. Examples of the kind of property sometimes invoked in this regard include 'flexibility', 'reversibility', 'resilience', 'stability' and 'robustness'.

Of course, the practical operationalising of such concepts presents many challenges which are far from resolved. Existing understandings in the context of the regulation of technological risk and uncertainty tend to be both rudimentary and ambiguous. Nevertheless, it seems quite clear that – all else being equal – the degree to which a particular technological strategy may be adapted to avoid adverse consequences as they become evident (ie: *flexibility*), is a factor worthy of consideration in any 'precautionary' approach to appraisal [190]. Likewise, the degree to which a technological commitment may be *reversed* in the event that unexpected impacts come to light is also a property with some precautionary benefits [191]. Not can it be assumed that high performance in terms of orthodox risk or environmental assessment will necessarily correspond with *resilience* under changing circumstances [192] or with *stability* or *robustness* to changes in the way the appraisal is framed or the way different issues are prioritised [193]. Such properties may thus be seen to warrant some attention under a precautionary approach to regulatory appraisal which would at least be entirely consistent with (if not directly contributing to) the maintenance of scientific 'rigour'.

6.12 Allow Iteration, Reflexivity and Open-Endedness in Appraisal

There is sometimes a tendency to represent an appraisal process such as risk assessment as a 'once-through' linear procedure, starting with the collection of positive empirical 'data' and proceeding to the obtaining of normative 'results'. However, the intimate inter-connectedness of option definitions, framing assumptions and value judgements which have already been commented on in this paper underscore the need for appraisal to be recognised explicitly as iterative in nature. This is especially the case where it is argued that the crucial output of appraisal lies in the systematic revealing of the sensitivities governing the relationship between final notions of performance and initial framing assumptions. The business of exploring such sensitivities is intrinsically iterative in nature, thus implying a cyclical rather than a linear metaphor for the process of appraisal as a whole.

One particular rationale for upholding the iterative and reflexive character of appraisal which arises both under 'scientific' and 'precautionary' perspectives concerns the importance of monitoring. Although an entire topic in itself, and often not included as an aspect of risk assessment or environmental appraisal, the sustained monitoring of the consequences of regulatory decisions forms an obvious and crucial source of

[190] Genus, 1995a, 1995b; Killick 1995; Andrews, 1995

[191] Brooks, 1986; Martin, 1994; Wallner et al, 1996

[192] Holling, 1994; Allen, 1994; Ku, 1995; Norton, 1995; Farber, 1995

[193] May, 1972; Stuart, 1984; Sastry, 1989; Law and Bijker, 1992

information which becomes a necessary part of the appraisal informing the development of future regulatory decisions. The importance of such measures is currently quite well recognised in the existing proposals for the revision of EC regulation of releases of genetically modified crops [194]. However, the efficacy of monitoring as an indicator of future performance is highly contingent on the comparability of conditions. For instance, the senior regulator of releases to the environment of genetically modified crops in the UK has recently expressed concerns over the degree to which the monitoring of field trials provides information of wider relevance [195]. In this regard, it is important that the practice of monitoring not be seen to supercede other lessons discussed here for regulatory appraisal, such as the maintenance of humility in the face of ignorance.

Building on this, some of the sociological critiques of the more analytical approaches to appraisal have focused on the failure to acknowledge the essential reflexivity in the evaluation of contending technological options. For no party is it true that the way in which appraisal is approached is unrelated to the nature and context of the results which are obtained. All parties involved in an appraisal process – from sponsors, through the various specialist practitioners, to the audience and the critics – are themselves social actors with their own perceptions, values, interests and agency. From a sociological point of view, then, the question of 'strategic behaviour' thus becomes an essential issue – as much with respect to the researchers in an analytical study as to the participants in a deliberative process. Indeed, in the broadest sense, the process of appraisal is itself a strategic initiative situated among (and associated with) specific social interests. In this regard, the positive effects of this kind of 'antagonistic co-ordination' and 'social learning' between contending interests in the social appraisal process is addressed in more detail in a companion paper in this project [196].

For all these reasons, it may be argued that the inherently reflexive character of appraisal requires conscious and explicit reflection on the part of all parties engaged. The desirability of greater transparency (already addressed in this paper) is thus underscored. Aspirations to invisibility and claims to objectivity or transcendent authority in appraisal are unreflective and so ultimately likely to prove counterproductive, not only in relation to the effectiveness and efficiency of the appraisal process, but also (by polarising the issues and undermining trust) to the very parties harboring the interests ad making the claims.

6.13 Uphold the Primacy of Institutional Legitimacy and Political Accountability in Justification

A final common practical implication of 'scientific' and 'precautionary' approaches to regulatory appraisal concerns the overall political and institutional context within which this activity takes place. Although not properly undertaken as part of an appraisal process, regulatory decisions do have to be made. In a democratic society, such decisions need to be justified. There is no doubt that such decisions should be informed by the results of appraisal. The question is, however, to what extent can regulatory decision making be justified *solely* on the basis of appraisal? This applies equally whether appraisal is conducted by means of analysis such as risk assessment or under a broader-based deliberative framework such as that advocated here on the grounds of both 'science' and 'precaution'.

The crucial point emerging repeatedly in this report and which bears on this question concerns the intrinsic and unavoidable subjectivity and open-endedness of the regulatory appraisal process. No matter how complete or rigorous the analysis, nor how inclusive or exhaustive the associated deliberation, the determinants of a final decision will in many important respects remain essentially subjective. This is not to

[194] EC, 1998

[195] Beringer, 1998

[196] Rip, 1998.

say that ‘anything goes’ – with any decision being essentially as good as any other – but simply that a range of alternative assumptions might be defended as equally reasonable under different, and equally valid, contexts or perspectives. Such factors include, for instance:

i) the choosing and characterising of options;
ii) the selection, definition and prioritisation of appraisal criteria;
iii) the framing of the evaluation of individual options under individual criteria;
iv) the articulation and interpretation of uncertainties and ignorance; and
v) the consideration given to strategic factors such as diversity, flexibility and resilience.

Seen in this way, neither analysis nor deliberation can be seen necessarily fully to determine a particular decision. Although regulatory policies are, of course, undoubtedly usefully informed by analysis and deliberation, and though such analysis and deliberation may itself be evaluated as more or less systematic, complete or robust – the business of making real regulatory decisions over technologies such as energy options, chemicals or genetically modified crops will, in the end (and at some political level), require the exercise of individual or collective judgement on the part of the decision makers themselves. In a democratic society, such judgements are justified not simply by reference to the appraisal process, but in terms of the credibility, trust and mandate enjoyed by the institutions and individuals responsible for the resulting decisions. In this way, both ‘scientific’ and ‘precautionary’ approaches to regulatory appraisal may be seen not only to imply the complementarity of deliberation and analysis, but also the subordination of appraisal to the over-arching principles and structures of governance itself. In the end, neither ‘sound science’ nor a ‘Precautionary Principle’ can carry the proverbial can. The buck stops with institutional legitimacy and political accountability.

7 CONCLUSIONS

The Conservative British Prime Minister Winston Churchill was famous for his bullish attitudes He was hardly the paradigm example of what have later in some quarters come to be seen as post-modern anxieties over risk. And yet it is to a remark of Churchill's that a central theme of this report can be linked: "*science should be on tap not on top*" [197].

Such sentiments should not be taken to imply undue reservations over the achievements or value of scientific approaches to the problems of technological risk. Still less should they be seen as an expression of an anti-scientific perspective. Instead, they reflect the adoption of a measured, balanced, and, above all, *scientifically informed*, assessment of the proper role of science in the regulatory process. In this regard, the tensions apparent in some areas of the debate over science and precaution in environmental regulation, though very real, might better be explained in terms of divergent views on the social and cultural roles of science than as conflict between 'pro-' and 'anti-' scientific sentiments.

The purpose of the present paper has been to examine the relationship between 'precaution' and 'science based regulation' in the specific practical context of analytical approaches to risk assessment and environmental appraisal. The basic conclusions are quite readily expressed. Far from being in contradiction, the implementation of a precautionary approach can be entirely consistent with the most demanding principles of scientific rigour. Indeed, to the extent that the formal conditions of ignorance and incommensurability in probability and rational choice theory are recognised to be of some practical significance and yet not addressed by the orthodox techniques of risk assessment, the adoption of complementary 'precautionary' approaches to appraisal might reasonably be judged to be *more* scientifically rigorous than their rejection.

A potentially useful aid to the understanding of this apparent paradox is the concept of 'scientism'. This is a term developed in the sociology of science to refer to the extension of scientific discourse into other arenas where "*scientific language, techniques, approaches, models and metaphors (unproblematically established elsewhere) have previously been thought inapplicable*" [198]. Both science in general, and the specific scientific disciplines of risk assessment, are clearly indispensable in the practical business of regulatory appraisal. The question, however, is not whether they are *necessary*, but whether they are *sufficient* as a basis for regulatory appraisal. With respect to the particular issues of incommensurability and ignorance, it has been shown in this report that the concepts of probability and aggregation of preferences are quite simply inapplicable – in the most scientific of terms – to some of the most serious real-world problems of appraisal. In this sense, then, attempts to treat risk assessment as the only 'sound scientific' approach to regulatory appraisal are actually *scientistic*, but not scientific. Recognition of the value of precautionary approaches such as those discussed here, on the other hand, can be seen as *scientific* rather than scientistic.

In short, the particular complementary measures which are suggested by this analysis to be both jusified in the regulatory appraisal of technology both on grounds of 'precaution' and 'sound science' comprise the following:

- Broaden the scope of the regulatory appraisal of technological risk to include complex, synergistic and indirect effects as well as the associated public benefits.
- Acknowledge the intrinsically subjective character of the assumptions adopted in the framing of analysis.
- Maintain a culture of humility in the face of the many sources of uncertainty and ignorance in appraisal, expressed by means such as 'ignorance audits', 'error margins' and 'minimax criteria'.

[197] Lindsay, 1995:217

[198] Cameron and Edge, 1979:6-8, See also Barnes and Edge, 1982.

- Complement and inform analysis with procedures for inclusive deliberation by stakeholders, such as consensus conferences citizen's juries, focus groups and deliberative polls.
- Conduct appraisal on a comparative rather than a case-by-case basis, including account of a variety of technological and policy options and the cumulative effects across different cases.
- Harness the potential of well-established straightforward multi-criteria appraisal techniques as a way of combining technical issues and fundamentally subjective matters of value judgement.
- Express appraisal results not as single discrete numerical values, but using sensitivity analysis systematically to 'map' the consequences of different value judgements and framing assumptions.
- Prioritise the qualities of transparency and simplicity in selecting appraisal methods and provide for effective extended peer review.
- Focus appraisal on the dynamics of portfolios of technologies rather than on individual options.
- Take account of qualitative strategic factors in technological strategies (like flexibility, reversibility and resilience).
- Allow iteration, reflexivity and open-endedness in the interactions between sustained scientific monitoring, continued analysis and inclusive deliberation in appraisal.
- Uphold the primacy of institutional legitimacy and political accountability in the final justification of regulatory decisions.

In short, the conclusion is that pursuit of 'precautionary' measures such as these offers the best way of carrying forward a 'science based' approach to the regulatory appraisal of technological risk.

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CONTRIBUTIONS FROM SOCIAL STUDIES OF SCIENCE AND CONSTRUCTIVE TECHNOLOGY ASSESSMENT

Arie Rip

CONTENTS

1. Introduction

What started out as a paper outlining recent work in the social studies of science and technology, and its possible contribution to issues of technological risk and the management of uncertainty has become an essay on tractability. And in particular, on how problems that may be intractable in principle still become tractable in practice.

There are costs and risks associated with achieving tractability, because it reduces problems rather than that it solves them, and what has been "reduced away" may return at an inopportune moment. But there are also major advantages, especially when the idea of ongoing and productive practices is taken seriously. Tractability cannot be laid down by law, but has to be achieved in practice, and be maintained through the rules, formal and informal, that emerge in such practices.

This may sound like a compromise, but it is not a compromise to look down upon as being a second-best solution. The intellectual achievements of science are built on such a compromise. Consider the intractable problem of formulating knowledge claims with universal validity, and proving them, when one cannot do more than experiments of limited scope, in certain places and at certain times. Still, an edifice of scientific knowledge has been built on these precarious foundations.

Philosophers of science have worried about the strength of the foundations, and attempted to specify methodologies for building solid edifices. Karl Popper's critical rationalism, with its sociological complement of "organized scepticism" as a rule in the social system of science, appear to capture important parts of how the productive practice of building the edifice actually proceeds. As Donald Campbell, the well-known psychologist, methodologist and epistemologist, has shown, there is a compromise involved, in the sense that scientific communities need what he calls "tribal norms" to bind them together and make the epistemologically important norms forceful. Competition for reputation would be one such tribal norm. (Campbell 1979)

Issues of technological risk and the management of uncertainty are in many respects intractable problems. Other papers in this ESTO project indicate specific ways to reduce intractability, for example by creating a typology of risk situations and drawing out implications for action (Renn & Klinke). Such an approach decomposes the intractability in two parts: within each type and across the types. Given a type and its specific properties, action implications can be articulated and optimized. The question of choosing the type which applies best to the actual situation is of a different kind (and might be contested).

A similar approach is possible for the issue of scientific expertise. Alvin Weinberg's influential essay on trans-science (Weinberg 1972) creates two types, science and trans-science, and discusses the different ways these are organized. Silvio Funtowicz and Jerry Ravetz identified three types, including the intriguingly named post-normal science (e.g. Ravetz 1987; 1992; Funtowicz and Ravetz 1993). Such typologies are directly relevant to debates about, and concrete attempts to set up, arrangements to let science contribute to policy. Further typologies have been made, often using consensus/dissensus as a key dimension.

Starting from another angle, one may inquire into the nature and functioning of arrangements to create some tractability, for example in regulating for occupational health and safety, and how to improve such arrangements. Following this train of thought, it is a design challenge to help create arrangements and processes which achieve tractability. I see 'design' here both as an intentional activity with a product that must be implemented, and as a process of *de facto* design in which new practices, procedures, norms, and institutions emerge. Such "dual use" of the concept is analogous to the way Harry Mintzberg, the organization and management scholar, discusses strategy: intentional strategy, developed as such and to be implemented with some effort (if at all), but also what he calls 'pattern strategy', the goals and approaches implicit in the actions and interactions as they occur, and which can be, but need not be, made explicit and reflected upon (Mintzberg, Quinn and Goshal (1998), p. 15). Similarly, the methodologies of science can be seen as epistemological strategies, and they have evolved as pattern strategies: part of productive practices and interactions, and then reflected upon, by practitioners and by philosophers. Thus, it is not just a matter of dual use of a concept, like strategy or design, by an analyst; the duality is out there in the practices of actors and how they attempt to get some grip on their situation.

The use of a design perspective implies that my canvas must be broader than social studies of science and technology as such. Organizational sociology, institutional economics, public administration and management studies can, and increasingly do, contribute. In a brief paper, I cannot do justice to all relevant insights and experiences. My presentation and argument will be informed by such literatures, and I will occasionally refer to them.

In fact, also for social studies of science and technology I cannot cover everything that is relevant. For the reader interested in an overview, I refer to handbooks in the field (Spiegel-Rösing and Price 1976; Jasanoff, Markle, Petersen & Pinch 1995) and two overviews commissioned as part of a project on the state-of-the-art in social sciences relevant to issues of global climate change (Jasanoff and Wynne 1998; Rip and Kemp 1998).

In science and technology studies (I will delete 'social' because the studies discuss science and technology broadly, including epistemological, economic and cultural aspects), the questions of scientific knowledge and expertise, uncertainty and solidity, are studied as *de facto* design processes: how is expertise built, how are uncertainties reduced? In section 1, I will locate these insights as contributions to the design of science-based regulation and other science-for-policy arrangements. I will also introduce a "base line" other than consenus and certainty by starting from controversies as the common state of affairs and inquire into processes of closure, rather than assume that somehow, somewhere, there is a domain of consensual and solid knowledge that can be tapped unproblematically.

In section 2, I take up the idea of design principles, one example being the precautionary principle. This and other such principles are intentional principles. As a principle, and when developed into specific measures and rules, there is a substantial component, and a "tribal norm" component. Both should be taken into account to achieve productive implementation. For emergent principles, derived from *de facto* design patterns (one example is the role of insurance), the dual character is present from the beginning.

The broad argument in section 2 is an intermezzo which allows me to discuss, in section 3, the approach of Constructive Technology Assessment (CTA) as a specific design approach for the development and introduction of new technology: broadening the learning processes involved, emphasizing anticipation and the importance of thinking and acting in terms of "increments of precaution." The experiences with this approach, building on insight into the socio-technical dynamics of technological change and its embedment in society, also show the importance of modulation (of ongoing processes) rather than central policy formulation and implementation (which assumes that the central actor can somehow remain an outsider to the dynamics). Just like intentional strategies are always necessarily part of emerging pattern strategies, and modulate the pattern, so intentional design is part of *de facto* design and modulates it.

I continue this line of thinking by presenting, in section 4, findings about broader and longer-term developments in the culture of our risk societies. The nature of concrete regulation, risk assessment, and risk management, appears to be shaped by contexts and their histories. These can be enabling: new and sometimes better approaches emerge; contexts can also constrain, however. Intentional design at the macro-level is difficult (although there are examples, up to the constitutions of nation states). Some patterns, when recognized for what they are, can be taken up and exploited. I shall identify agonistic coordination as one such pattern.

In the fifth and final section I collect insights from the earlier sections which are not immediate tools or measures, nor principles from which they can be derived, but meta-norms. One example is the need to avoid rigidities, in particular dichotomy traps.

2. Knowledge, uncertainty and closure

Given the advent and dominance of science-based regulation, it is important to know about the nature (and dynamics) of science, and in particular, about the form and productivity of arrangements to "base" regulation in science (and about science-for-policy arrangements more generally). One traditional arrangement is to have the science base separate from the decision making. In concrete arrangements, the productivity of the set-up does not necessarily depend on the strict spearation of the domains. The lesson of the Dutch arrangement for regulating chemicals in the workplace is that "boundary work" is necessary, repairing the uncertainties and limitations in knowledge, in advice and in the division of labour in the arrangement (see box 1).

Case study: quality assurance through mandate and repair work (study by Roland Bal (1999), drawing on sociology of organizations and sociology of science)

Regulation of chemicals with respect to occupational health and safety has scientific inputs in all countries (including international exchange and mimesis). In the Netherlands, standard setting is organized to be science-based by distinguishing different actors and their legitimate inputs, and starting the sequence with the scientific experts. There is an overall mandate which specifies domains of responsibility: scientific advice (primarily based on toxicology), socio-economic trade-offs, and final bureaucratic and political responsibility for authoritative standard setting. Each of the domains is organized, the first two with special committees (of experts and stakeholders, respectively), and the decision process is to be sequential, with the committee of experts delivering packaged advice to the socio-economic committee, which adds its advice on feasibility, while finally staff of the Ministry for Social Affairs prepares the document which will set the standard.

The Dutch set-up is productive (in terms of number of standards set, their quality, and the limited occurrence of controversy), and perhaps surprisingly so, given the ideology of strict separation of responsibilities. Based on international comparisons and detailed cases of standard setting in the Netherlands, Bal concludes that the productivity is realized because of the space for repair work (in particular boundary work, actual and anticipatory). He also shows that some of the risk concepts and approaches that were developed derive from the need to manage boundaries. Recent developments, for example carcinogenics and the question whether they have a no-effect level, put pressure on the institutionalized boundaries (institutionalized in the administrative as well as the sociological sense). According to Bal, the quality assurance system still has sufficient flexibility to accommodate these questions, but he also indicates that existing concepts (in particular, standards based on threshold values) cannot do all the coordination work that is necessary in the risk society.

Box 1. Mandated standard setting and regulation

From this point of view, the changes in the working arrangements of the International Panel on Climate Change between its 1990 report and its 1996 report, now including stakeholders (non-governmental organizations as well as governmental policy advisers) in the review and deliberative process, is not (just) a matter of bowing to external pressures (Jasanoff and Wynne 1998; p. 21). It is (also) a way of doing boundary work and maintaining productivity.

I am using 'productivity' here without defining the concept, because I do not want, at this stage, prejudge the issue which dimensions or aspects have to be given precedence. I shall use studies of controversies (in science, and science-related controversies in society) to indicate how some closure is achieved and how certain findings and insights become robust (consolidated and internally articulated).

Key areas of science and technology studies relevant to these issues are the studies of expert knowledge, how it is achieved, and what constitutes its solidity; the management of uncertainty within science and towards broader audiences, and the relationship with lay knowledge; and socio-cognitive processes of reduction of uncertainty, up to "closure". Cultural theory (Douglas 1982; Douglas and Wildavsky 1982; Schwarz and Thompson 1990) has addressed such issues as well, and there are, in fact, a number of studies of science which use cultural theory. I shall not discuss the contribution of cultural theory in any detail, because my interest here is in socio-cognitive processes rather than explanation in terms of a typology.

2.1. Scientific knowledge

The basic point, made by philosophers of science, and supported through detailed historical and sociological case studies, is that scientific knowledge is "underdetermined". There is no absolute assurance that later findings, and/or new arguments, will not undermine present achievements. There are degrees of solidity, of course. But the nature of scientific observation and experiment, and the precarious shift from specific findings to more general knowledge claims, always leave openings for doubt and further checks. Closure of the quest is a practical matter, not a logical step.

Logically, the *ceteris paribus* problem undermines any attempt at universality of knowledge claims. You know what you have observed in this experiment, here and now. But are the circumstancves in another experiment (of your own, of another researcher) exactly the same? You can try to control the conditions and thus make the *ceteris* the same -- but you cannot control for what you do not know about. In practice, iterations between preliminary understanding and first attempts at control, often converge to a stable alignment between working experiments and scientific understanding based upon them (Rip 1982, Collins 1985).

A subsequent issue now emerges: experiments that work do so under specific circumstances. Experiments on effects of release of GMO in the soil, using a "micro-cosm" (Cambrosio et al. 1992) tell you a lot about what happens in the micro-cosm, but not necessarily about what happens in the wider world. When society (and the world) is taken as the laboratory (Krohn and Weyer 1994), it is impossible to do fully controlled experiments. Learning through trial & error occurs, but has its risks (when the trials are dangerous) and are, epistemologically, limited because they follow a particular learning trajectory. The example of the introduction of new medical drugs and the monitoring of effects shows the possibilities and as well as the limitations (i.e. risks) of the approach.

The implications for the issue of environmental release of genetically modified organisms (GMO) are brought out vividly in an observation by Von Schomberg:

> The task for policy is to translate the precautionary assumptions of the legislation which is based on a 'case-by-case' and 'step-by-step' procedure, into a mangaeable practice that acknowledges these assumptions and make a science-informed learning process possible. (...) What intended effects can be 'manageable', on the one hand, and provide us, on the other hand, with usable information on the behaviour of GMOs that would provide a basis for risk assessment? What intended effects will be acceptable effects?
>
> These questions cannot be answered yet, since not only the appeal to science implies a reduction of the problem, the manageability criterion, imposed by regulatory policy on the practice of field experiments has produced another possibly reductionist position: manageability has been equated with planning safe experiments from which we cannot learn enough. (Von Schomberg, 1996; 149)

(I note in passing that the phrase "science-informed learning processes" in this quote links the observation with my general approach. Cf. also below, section 3, on the Constructive TA approach to the introduction of new technology.)

The second main reason for scientific knowledge claims being underdetermined is that to understand what you see, observe, measure, you need a "theory" of the situation (the experiment, the apparatus), separate from the theory of the phenomena. A striking example, studied in detail by Galison (1987), are high-energy physics experiments. For new and/or contested observations, which do not fit with present understanding, the direction to go cannot be decided unambiguously: it may be that the theory of the situation is OK but the theory of the phenomena to be measured/observed is wrong -- or the other way around. In the experiments in CERN and other particle accelerator facilities, the background phenomena and apparatus are modeled with the help of a theory of the experiment. The CERN researchers only "found" a new particle when they changed their theory of the experiment.

Modeling background phenomena is also important for policy-relevant science, for example when environmental effects have to be estimated. If the choices involved remain invisible, the pretenses that have gone into the final results will remain underexposed. Criticism from scientists or other involved actors may be necessary. In general, findings should be presented also in terms of the choices made to obtain them. Funtowicz and Ravetz tried to systematize this idea by adding 'pedigree' to their list of indications of uncertainty. In quality control terminology, one could speak of 'traceability' of knowledge packages.

From a general and philosophical concern about underdetermination of scientific knowledge claims, we have now progressed to consideration of the actual trajectories followed in the attempts to produce more or less solid findings. One can then inquire into the nature of such trajectories, and the *de facto* requirements on them, given their history and context. Before I address such questions in the next two subsections, I note that the definition and pursuit of specific trajectories are often predicated on a partial closure of broader questions. In a sense, one has to put on blinders to make concrete progress -- hopefully in the right direction!

In this respect, Von Schomberg (1997)'s distinction between empirical-analytical problems and broader epistemic problems is useful. His (and mine) point is then that empirical-analytical approaches, beloved by users because they seem to promise solid, or "sound," results, are predicated on the (contingent) closure of epistemic problems. The study of, and debate about, environmental release of GMOs again provides examples (see Box 2).

The debate on genetically modified organisms (GMO) included consideration of possible evolutionary impacts. The discussion had (and has) broader cultural overtones: "playing havoc with creation." The scientific issue could not be settled by empirical and logical arguments. The starting point is obvious enough: "Many organisms under consideration for release will be designed to overcome natural limiting factors (..) they are aimed at the very boundary and definition of the ecological roles of particular species." (Colwell et al 1985, quoted in Von Schomberg 1997; 66) A dominant reaction, reflected in one of the conclusions of a particpatory technology assessment exercise on transgenic herbicide-resistant crops, is: "In contrast to conventional breeding, genetic engineering can transfer genes between species which are widely different in evolutionary terms. However, the greater the evolutionary distance between the species, the lower the probability that they will somehow converge. Therefore, the further genetic engineering moves beyond the limits of traditional breeding, the less reason is there to fear that it could trigger evolutionary processes which end up in species mixtures and a loss of differentiation in the species spectrum." (Van den Daele et al. 1997; 34)
From the second statement on, one sees plausibility arguments rather than empirical-analytical argument -- it would be difficult to do better anyway. The policy-relevant conclusion can be contested, and has been contested in various ways. For example: " The fundamental premiss of evolutionary theory is that natural selection (..) operates on genetic alterations (...) to produce evolutionary change. It follows that at least some genetic alterations imporve the abilities of organisms to survive, to reproduce, compete for resources, or invade new habitats (...). A general assertion that genetic alterations (...) always lower the fitness of organisms is therefore not warranted and runs counter top basic evolutionary principles." (Sharples 1985, quoted in Von Schomberg 1997; 75-76)
The debate is furhter complicated by the question whether genetic engineering is "special", or just like traditional breeding. The latter suggestion can be used to assuage fears (nothing unusual is happening), but can also be turned around, because "even traditional breeding has not been ecologically trouble-free" (Colwell et al 1985, quoted in Von Schomberg 1997; 66)

Box 2 Example of an epistemic problem, and related policy debate

When epistemic problems are foregrounded, the underdeterminedness of scientific knowledge is not just a practical problem, to be handled according to the routines of "normal science", but is the focus of the debate. In what Thomas Kuhn called 'scientific revolutions', epistemic issues are highlighted. When, somehow, a new paradigm emerges and becomes dominant, epistemic debate is backgrounded -- until persistent anomalies thrown up in the course of research within the paradigm lead to a renewal of the debate. In other words, the closure of broader questions can be opened up again through the work along the trajectory made possible by this closure. As the debate on risks of GMOs shows, societal and cultural considerations -- always implicated in epistemic debates -- are other occasions for opening up the broader debate.

2.2. Uncertainty and solidity

In his study of missile guidance technology, Donald MacKenzie addressed the issue of uncertainties, for example in the guidance system and in the assurance of the missile reaching its target, and showed that tolerance for uncertainty differs across various relevant groups (MacKenzie 1990; 370-372). MacKenzie drew on earlier studies in the sociology of science (in particular by Harry Collins, cf. his 1985), and his basic idea has subsequently been applied by Steve Woolgar and Arie Rip to tolerance of uncertainty in scientific results and expertise in general.

Uncertainty can be, and generally is, tolerated within a scientific specialty, especially by the 'core set' working at the research front. When knowledge is to be used in professional activities (in another scientific specialty, in professional practice, in preparing policies and decisions), however, actors want it to be as solid as possible. (Except in situations when there is an interest in finding an opening for alternatives, and uncertainties are welcomed). When scientific findings are disseminated to broader audiences, the link with action is absent, or indirect, and there is more tolerance (or perhaps just indifference) for uncertainty. A graph with tolerance to uncertainty on the vertical axis, and closeness to knowledge production on the horizontal axis, has the shape of an animal feed trough -- the trough of uncertainty.

One immediate implication is that pressure to reduce uncertainty, and to achieve 'closure,' is different in the three contexts -- the tribal norms are different for different tribes. One such difference relates to the time horizon for action. Within a scientific specialty, the quest for "the" truth has no definite time limit (even if there may be, in competitive areas, a race to be first). For practical purposes, whether these are getting an instrument to work in an experiment, or expert advice contributing to a decision-making process, to have 'solid' knowledge available has to fit time schedules of action. In the public sphere, it is important to enable concerted action -- cf. interest in consensus conferences, and similar attempts to separate the 'solid' from the still uncertain. Another indicator is the impatience of decision makers and politicians with the conditional statements of scientific experts and their "on the one hand/on the other hand" vacillation.

To apply the norms of the latter tribe to the work within a scientific specialty may well be counter-productive. And even counter-productive to the goals of the policy tribe itself. The pressure for certainty includes a preference for 'solid facts' rather than theories and models. This creates a problem when anticipatory assessments have to be made, for which by definition observation or measurement is impossible. US Congressman George E. Brown, Jr. analysed the hearings convened by the Republican-dominated Energy and Environment Subcommittee, and concluded: "again and again, like a mantra, we heard calls for 'sound science' from Members who had little or no experience of what science does and how it progresses." Brown (1996) shows that 'sound science' turns out to mean 'empirical science,' in the sense of direct observation rather than models and statistical analysis. When Subcommittee members argue that the government should intervene on environmental problems only after incontrovertible direct observations confirm the problem's existence, Brown warns that such a standard (of 'sound science') would make it impossible to prepare for environmental harms in advance.

Early warning is speculative by definition, but it is one ingredient (together with early listening) of the learning society. To make it an integral part, new practices and informal as well as formal rules have to evolve, because neither the tribal norms of science, nor the tribal norms of policy are adequate to handle the complexity of the situation. Quality assurance for early warning processes has to do with due process, but also with standing (not everybody's warning is worth pursuing) and with strategic action (actors can take up the cloak of Cassandra for other purposes than warning in the public interest).

Sound science as the base of regulation is not exempt from such practical considerations: how "sound" can you be, and should you be? The question of soundness is as much a social-organisational challenge as an epistemological issue. There are concerns about working with animal models or other models (in standard setting for chemicals), about extrapolations and about arguments based on analogies, which can only be resolved pragmatically. The safety net is not in the science as such (which is underdetermined) but in an assurance of a minimal 'soundness' provided by the organization of the standard-setting procedure and the quality assurance (linked to accountability) that goes with it. (See Box 1)

With the advent of computer modeling, a new range of possibilities to support decision making and action, as well as further sources of uncertainties have emerged. When in late 1995 the report of the International Panel on Climate Change was made public, it claimed a "discernible" influence of human activities on global climate change; its claim (and the advances compared with its 1990 report) was based on the increased sophistication of climate change models rather than on measurement (which would be difficult anyway). The socio-political stakes involved were visible in the debate on the exact phrasing, which led to a change from the original statement about "appreciable influence" to the one quoted above. The latter, clearly, can be defended better than the former, not necessarily because it is sounder science, but because it reflects the overall balance of cognitive (scientific), moral and political forces.

These considerations are also relevant to the precautionary principle: As Michael Rogers (1998) has argued, application of a precautionary principle requires the drawing up of scenarios for possible chains of events. Such scenarios used to be primarily narrative (and linked to cultural repertoires and images, cf. section 4 on runaway organisms), but are now explicated (Renn and Klinke, in the part of their report which discusses GMOs, actually offer such scenarios in subsections 2.1-2.4) Scenarios can be partially implemented in computer models. Apart from the status conferred to findings and arguments be having them spewed out by a computer, implementation in a computer has the advantage of forcing actors to be more explicit about magnitudes and relationships, and searching for (better) values for them. The disadvantage is that only those factors and relations are taken into consideration which fall within the scope of the computer model.

Recent social studies of science have concentrated on the actual "doing" of science, and have re-interpreted quality of science and validity of eventual results in terms of the processes involved rather than characteristics of the (de-contextualized) outcomes themselves. Some scholars in social studies of science, in a polemical stance against earlier, Whiggish views of science, have emphasized contingency and relativism, which made them an easy prey for the "science warriors" (like Gross and Levitt 1994). The real point is that quality and validity are made. One can speak of 'robustness' of the construction in relation to its solidity (and resiliency) with respect to disturbances which may occur in the practice in which the construction functions. (This version of constructivism is similar to the pragmatic constructivism of engineers building bridges and power plants; cf. Rip 1994.)

While essentially pragmatic, this view does not do away with traditional approaches to validity in science, which emphasize replicability and generalizability, but includes them, and adds the point that replication and generalization require work, especially an infrastructure which allows circulation of bodies and instruments and texts (this terminology relates to actor-network theory). One clear advantage of this broader view is that it allows a diagnosis of present-day changes in science (increased heterogeneity and intervention by others than immediate (competing) colleagues) which transcends conservative complaints or triumphalist embracing of the new, and allows a discussion of quality (Rip 1997, 1998; see also Ravetz).

While the scholarly record of science studies is impressive, there are certain limitations as well. In particular, the emphasis has been on demonstrating the insuffiency of earlier views, on the basis of theoretical arguments (and some polemics) and illustrative case studies. The positive version of the constructivist, socio-cognitive approach is less well developed, and the translation into tools and other support for practices is often of a handwaving kind.

Box 3 The so-called relativism promoted by science studies

2.3. Controversies, robustness and learning

As is already clear from the examples in the preceding subsections, and has been shown in detail in a large number of case studies in social studies of science, solidity of scientific findings is a matter of alignment: alignment of controlled observations and theoretical considerations, as well as cultural and moral values, interests and circumstances. Some scholars have rephrased this point in terms of a relativist notion of truth, but that is not my intention (and would get me entangled, unnecessarily, in what has been called the Science Wars; see Box 3).

Closure in such alignment processes can be sought explicitly, but is also the *de facto* outcome of ongoing socio-cognitive processes. To trace such processes and their outcomes, agenda-building analysis has been used to good effect. The 'state of the art' in a scientific specialty or domain of research reflects the specifics of the earlier socio-cognitive processes. A good example is how the state of stratosphere research in the 1960s and early 1970s reflected efforts to address concerns about effects of supersonic transport aircraft, which then shaped the possibilities for further research as well as identification of risks. In particular, Rowland and Molina's 1974 early warning about possible damage to the ozone layer from chlorofluorocarbons was predicated on data and insights from this trajectory (Callon and Rip 1992; Rip 1992).

The kind of learning involved in and through the alignment processes is open-ended, because nobody knows the 'right' answers. It is also collective, rather than individual learning. For this reason, it has sometimes been called 'repertoire learning.' This phrase is particularly useful when one studies controversies and their outcomes, within science as well as science-related controversies in society. As I have shown for a number of cases, including the smoking-health link and risks of recombinant DNA research (Rip 1986), the processes and outcomes cannot be understood as the resolution of an issue through knowledge alone (or, for that matter, as the consequence of dominant interests and their interplay alone), but results from alignment of findings, arguments, perceptions, interests, and dominant values. The eventual alignment then creates a repertoire of considerations which are difficult to go against. In that sense, the outcome is robust (even if it can be undermined when new arguments, interests, or values unravel the existing alignment).

Robustness can be explicated as the combination of consolidation and well-articulated alignment. The smoking-health link, for example, was implicated in the prohibition of smoking in some USA states around the turn of the century, the argument being that smoking is what morally depraved individuals do (so it must be prohibited) and will lead to diseases (as punsihment for their sins). This not very well articulated alignment broke down in and after the first world war, when the cultural aspects of smoking cigarettes shifted. During the war, citizen groups started to send cigarettes to soldiers because the cigarette was an "indispensable comfort to the men." Moral associations now became positive, the cigarette being identified with "quiet dignity, courage, and dedication above all." (Troyer and Markle 1983, p. 40-41) In contrast, by the 1970s, after extended controversies, the smoking-health link had been articulated in great detail, and cultural shifts (for example, the attempt to link smoking with individual freedom) could not undermine the "edifice" that had been constructed.

This brief analysis of repertoire learning and robustness of outcomes helps to understand controversies and their outcomes, as they occur. One can then apply this understanding to analyse controversies, to support the construction of robust knowledge, and turn it into suggestions how to stimulate open-ended learning.

An example is the analysis of the force of arguments and positions in a debate, in the case of hearings and consensus workshops on underground storage of radio-active waste (Rip, Smit and Van der Meulen, 1995). This kind of analysis will also be applicable to heterogeneous bodies of scientific, professional and policy publications, for example in the case of Mad Cow's Disease, and could, if performed in real time, help to identify early warnings and contribute to their quality control. An European Union funded project, BASES, coordinated by Pierre-Benoit Joly (Grenoble), is exploring the retrospective version of such an analysis.

As to suggestions, there is the observation that collective learning does not occur automatically: it takes an effort, and in addition, individuals and groups often try to avoid heterogeneous and agonistic interactions which challenge them. A 'forceful focus' is necessary to put actors in motion and have them interact to articulate and consolidate socio-cognitive alignment. An example of a 'forceful focus' is an agency's declaration of intention to regulate (as the US Environmental Protection Agency can do -- cf. the extended example in Rip 1986). In general, the prospect of a formally or *de facto* authoritative decision induces positioning and lobbying, always linked with arguments and findings, and thus creates a measure of learning. If one recognizes such processes for what they are, one can try and improve their course. Conflicts may then be welcomed as an incentive to learn, rather than that they should be mediated and massaged away. One example of such an effect is that the use of Technology Assessment reports and uptake of arguments contained in them by the US Congress was higher when there was a controversy (Whiteman 1982).

Let me put this point more forcefully. For learning to occur, it is not necessary that shared views and common interests emerge. In contests and in battles, there is an element of agonistic co-ordination. The simple fact of knowing that it is a battle (and not a military exercise or a fox hunt) implies specific co-ordination: there must be some rules of the battleground, there is recognition of who are the allies and who are the opponents. This reduces uncertainty about who is who in the (presumed) battle.

Antagonistic (and in general, agonistic) struggles provide co-ordination and learning: they force actors to articulate the merits of their position, to search for arguments and counter-arguments, and to commission special research. So after some time, there is better understanding of the issues, and potentially, intellectual and other resources for more adequate action. Such struggles can also lead to an impasse, when parties limit themselves to mutual labeling the other as contemptibly wrong. Within science, controversies can similarly become unproductive when in the epistemic as well as tribal process of organized scepticism insider-outsider or regular-deviant labeling obliterates other interactions.

In science studies, many within-science controversies have been reconstructed and followed. The strength of intellectual vested interests is very striking: new theories, it has been said (e.g. for quantum theory in physics), win out only because the adherents to the old theory die, or fade away. At the same time, arguments about observations and explanations are part of the struggle. In other words, the learning processes have a social as well as a cognitive component. For learning processes more generally, the same will hold. One suggestion that can be drawn from the insights of science studies is about the role of boundary work, translating insider interactions where contingent considerations are acceptable, into a rationalistic repertoire for external presentation and legitimation (Bal 1999). The dynamics of scientific research and the resulting knowledge claims reside in the combination of contingent and rationalistic repertoires. In controversies, protagonists will often use a rationalistic repertoire to accuse the other side of being "un-scientific," and thus have no standing. As a strategy, it may be successful in the short run, but it reduces opportunities for learning. Policy scholars and analysts are taking up the suggestion that interest struggles and argumentative battles have to go together (Hoppe and Peters 1998).

These insights and further thoughts allow a broader, socio-cognitive perspective on the role of science, but also on the force of principles, including preautionary principles. Their force derives from their being aligned in networks of findings, arguments, perceptions, interests, values, infrastructures, sometimes also artefacts. Principles can work only as principles-in-context.

3. Design principles

In the socio-cognitive or 'dual' perspective set out in section 1, social, organisational and political arrangements are as important as the substantive (scientific or cognitive) aspects. In other words, arguments and debates cannot be short-circuited by referring to nature or the world out there, speaking to us in an unambiguous manner and telling us how to act. The particular way nature, or the world, speaks to us is part of arrangements that have emerged.

This makes it all the more important that such arrangements work well. The question is then how to devise and design productive arrangements. Two main routes can be distinguished: devise a productive approach as such and try to implement it; or reflect on what has emerged in practice and try to build on it and improve it.

An example of the first route is how the precautionary principle started as an external input, and is now being implemented in national, European Union, and international regulation. An example of the second route, an emergent design principle, is the role of insurance. While some analysts have argued that insurance only works when rules or regulations have been established, and cannot, therefore, be seen as an emergent arrangement itself, this is only half of the story. Insurers are keenly interested in risks, and prepare the grounds for new rules and regulations. The dominant approach to risk assessment, specifying risk as (dangerous) effect times probability of occurrence, originated the need to specify the scope of insurance in nuclear power generation (Rip 1986). Similar dynamics now occur in relation to weather & climate related risks, and actual damages.

> Reinsurer Munich Re just reported that 1998, the warmest year since worldwide records started about 150 years ago, was also the second worst for economic damage caused by natural catastrophes -- more than $90 billion worth. (...) (...)
> So insurers must be willing to support climate science and the kind of computing power needed to get inside worldwide weather patterns. The cost, though high, is what the industry must pay to safeguard its financial future. (Reynolds 1999)

For GMOs, the role of insurance is not as visible, but it must play a part.

In this section, I will limit myself to discuss the advantanges of looking at the precautionary principle as an intentional design principle, and then briefly consider other interesting design principles.

3.1 The precautionary principle

Discussions of precautionary principles quickly get into ideological debates (in cultural theory, these would be debates between sectists and entrepreneurs, cf. Douglas and Wildavsky 1982). The fact that a version of a precautionary principle is now part of regulation indicates that (again in Mary Douglas's terminology) hierarchists have accepted this addition to their regulatory arsenal. To make it work, however, more is necessary. Principles can easily create oppositions and rigidities -- dichotomy traps --, and should therefore always be complemented by repair work in ongoing practices.

The precautionary principle is better seen as an action shortcut, which enables decision making and action (whether there is uncertainty or not), while constraining it in certain directions. At present, it tends to occupy a higher moral ground than the alternative "go-ahead" principle, but both principles share the function of *de facto* reduction of uncertainty. Something is done, whether it is building a nuclear power plant or not building it (and probably building something else), and the world adapts to the new situation.

Now that the precautionary principle has emerged, it can be reflected upon and tried out as a *design principle*: a guideline which shapes further action and interaction, rather than an axiom (or decision rule) from which one can derive what to do and what not to do (this would go against the need to accommodate repair work). Thinking about the precautionary principle (and other principles, for that matter) in terms of design allows two interesting and important linkages: (1) a link with the literature on institutional design, and (2) a link with the literature on 'dominant design' in (technological) innovation.

In the literature on institutional design, Elinor Ostrom (1992)'s and others' distinction between three kinds of rules is usual, and useful: (a) the constitutional rules which specify the nature or charter of the institution; (b) the collective-choice rules, or rules of the game that characterizes the institution; (c) the operational or tactical rules, how to act productively within the institution (or game).

A precautionary principle can work at each of these three levels. If it is to be part of the charter, it is subject to ideological debate. At the tactical level, it becomes just one possible risk-taking (or risk avoiding) strategy. At the intermediate, collective-choice level concrete political institutions, including the European Union, attempt to articulate and authoritatively stabilize rules, often with a strong pragmatical component.

In institutional economics, another, partially overlapping threefold distinction is now common (following Douglass North 1990): (a) culture-embedded rules which shape the institution, but are often invisible; (b) constitutional rules, process rules, rules of standing (which are rules about interaction rules); (c) explicit rules, often decision rules. A precautionary principle can be a cultural archetype (part of a risk avoid-ance culture of collectivists or hierarchists as cultural theory would have it, or as an element in the "danger culture" of industrial society, as Rip (1991) suggests). It can also be a meta-rule about how to arrange interaction, regulation etc, or can be a decision rule to apply in specific cases.

This brief discussion is not meant to be definitive. It illustrates the importance of embedding or contextualizing a principle if one wants to evaluate and understand what it can and cannot do. It also shows that there are relevant literatures on which to draw for such an analysis, even if the exact categorizations do not coincide.

For institutional design (less so for institutional economics which focuses more on the functioning of rules than on how to create good ones), design approaches and methodologies have been articulated (Van Heffen et al 1999). These do not function like recipes, so that one cannot simply apply them to develop a precautionary principle into institutional arrangements and operational rules. They do point out the importance of negotiation with stakeholders to articulate the scope of the arrangements and rules, and to design specific arrangements and rules with an eye to implementability. A precautionary principle can then be a guideline for design, which shapes and selects further choices, in the same way that a policy framework guides policy decisions.

A further point can be made by drawing on the literature on technological design and innovation. Utterback, Abernathy, Clark and others (cf. Clark 1985) have shown that dominant designs emerge and provide the framework for further design and implementation lower down the design hierarchy (in interaction with concrete local practices -- so emerging alignments rather than a top-down dynamics). What we may be witnessing is a shift in the dominant policy culture leading to a new design hierarchy with a precautionary principle as a charter (Ostrom) and/or a culture-embedded guideline (North). Instead of deducing from a principle (precautionary or otherwise), it then is a matter of articulating the design hierarchy, it gradually becoming more concrete as it is embedded in concrete practices.

3.2. Other design principles

By way of example, I briefly consider another set of design principles and their rationale. In concrete design, as well as in discussion of design principles, it is always useful to consider a variety of possibilities, at least conceptually, and then choose which one to develop further.

An interesting set of principles was proposed by Zielhuis (the main architect of the arrangement for occupational health and safety standard setting in the Netherlands) around 1970 (Zielhuis 1972). His starting point was the way in which the substance (or condition) at issue affects the individual: is it essential for the organism's functioning (thus system-linked or intrinsic) or not. In the former case, the so-called ergonomic rule applies: the optimal balance is sought and the standard is set so as to maintain the balance. In the latter case, where the substance is foreign to the system, the hygienic rule is followed: the standard is set as low as possible, ideally zero.

Zielhuis then added a further consideration: substances foreign to the individual (say, a worker in a chemical plant, or somebody living in a polluted environment) might still be "intrinsic" for the functioning of society. These are then second-order system-linked, and a second-order ergonomic rule is appropriate. To apply such a rule, one needs to analyse the functioning of society, identify a more or less optimal balance, and set standards so as to keep that balance. In practice, this cannot be done by calculation. In the Dutch arrangement (see Box 1), the second committee with representatives of stakeholders is responsible for negotiating about the location of such a balance. Such a discursive approach, which inevitably mixes arguments, findeings, interests and values, produces alignment (cf. section 1).

The actual functioning of such a standard is more complicated because of dynamic reactions to the standard (and the process of setting standards) independent from the question whether the "right" balance had been estimated and translated into a standard, society would adapt to the situation, rearranging itself (Rip, Nieuwpoort, Verbeek 1972). What can also happen, and in practice does happen, is that the standard is not followed, or only marginally. As it were, a *de facto* standard reigns, which is sometimes recognized for what it is worth and leads to redefinition of the formal standard (Rip 1992).

Taking into account the dynamics makes the approach more complex, but also more realistic. The question then becomes how to arrange the process so that the dynamics are productive. Here, other design principles than the health-related ones of Zielhuis are necessary, and "intelligent trial & error" (Lindblom and Woodhouse 1993, esp. pp 131-135) or better, "intelligent trial & learning," is a good candidate. This contrasts with calculative approaches working toward an optimum outcome or optimum assessment. Many decision-support tools and approaches derive from systems approaches and thus tend to work toward optimization. (Multi-criteria analysis need not work this way, but often does. Addition of deliberative and interactive components, explored in a variety of projects including ones supported by the European Union, helps, but only partially.) Interestingly, in ecology, the approach of optimizing eco-systems has been recognized as creating instability, and population dynamics is taken to be the better starting point for managing complex systems. I see analogies with my analysis of socio-cognitive dynamics in the production of robust knowledge (section 1), and with the incremental learning approaches to be discussed under the heading of Constructive TA (section 3).

4. Constructive Technology Assessment

Technology Assessment can be seen as a type of policy analysis, supporting decision making about technology and technological projects. When made part of ongoing practices of technological development and its embedment in society, it becomes a design approach to the issues of handling or managing technology in society. This section (which draws on Kirejczyk and Rip 1999) sets out the overall approach.

4.1 Nature and evolution of Technology Assessment

Technology Assessment (TA) addresses new technology or new technological projects and attempts to anticipate effects which have not yet occurred. It is some future quality that is envisaged, not a present one that can be checked operationally. Secondly, as is clear in recent debates around genetic modification, the processes of quality care extend across a wide range of institutions and stakeholders, and often lead to further articulation of issues and to new alignments. Responsibilities cannot be set beforehand, but are one of the outcomes of the process.

The philosophy of Technology Assessment, in its various guises, is to reduce the human costs of >trial-and-error= learning of how to handle new technologies in society, by anticipation and feedback into decision making and practices. Thus, while distantiating itself from earlier ideologies of unalloyed progress through technology, it is still a typically modernist venture: we can do things better -- thanks to Technology Assessment.

Technology Assessment has been shaped, or at least coloured, by its origin and context (see box 4).

It was conceived, in the late 1960s, as an early warning system about the possible impacts of new technologies, both positive and negative. This required anticipation and analysis of broad range of technical,

> The ascent of Technology Assessment as a form of policy analysis and policy support is grounded in the changes that took place in the 1960s and 1970s. New social and cultural movements gave voice to concerns about the negative impacts of some technologies. National governments recognised the problematic nature of some technological developments as well and became interested in policies oriented towards restraining these impacts. The emergence of the environment as an issue in public debate, on the political agenda and as a challenge for government regulation, played an important role in this shift. So-called Environmental Impact Assessment studies have become institutionalized: officially required, and performed according to certain rules almost as if there an ISO standard had been developed. An additional impetus to Technology Assessment, and a factor in its revival during the 1980s, was the rise of idea that science and technology are strategic assets in international competition, in wealth creation more generally, for health and for sustainability. Technology Assessment can be used to articulate the contribution of different options to such goals and thus improve the choices being made. Such "picking the winners" Technology Assessment is actually practised by large industrial companies and R&D institutes. In the public domain, Technology Assessment had already become linked to mitigating undesirable effects of new technologies, and would now serve to broaden and balance the agenda of the debate on promotion and control of particular biotechnologies, and information and communication technologies, to mention the main examples.

Box 4. The evolution of Technology Assessment

economic, legal, cultural etc. impacts ahead of the introduction of a given technology. In order to do so, it was necessary to pin down the characteristics of the technology as much as possible, and focus on the desired and undesired impacts of the "given", though not yet realized, technology. For early warnings to have effect, the insights gained through anticipation had be fed back effectively into the decision making processes of actors involved in the introduction of new technologies, and in particular government agencies and representative bodies like parliaments or the US Congress, who are expected to consider the public interest. Smits and Leyten (1991) distinguish Awareness TA and Strategic TA, depending on whether the early warning serves agenda-building purposes or strategic decision-making.

In the government context, a key feature of the way modern societies handle the development and introduction of new technologies with their unknown effects is very visible: the institutional separation of activities aiming at the promotion of technological development and of those aiming at controlling the effects of this development. On the one hand, there are Ministries of Economic Affairs, or Trade and Industry, who stimulate the development and introduction of new technologies with a variety of measures and special funding. On the other hand, there are Ministries of Social Affairs and Environmental Affairs who carry out projects aiming at a long term reduction of pollution, of congestion and in general at minimising human and environmental damage in industrial society. Technology Assessment, as it evolved (and sometimes criticized as really being "technology harassment"), was part of this "two-track approach" (Rip, Misa & Schot 1995) rather than that it challenged the institutional separation or significantly contributed to bridging the gap between the two tracks. In terms of reducing the human costs of >trial-and-error= management of technology in society, other approaches, for example technology forcing through regulation, i.e. specifying standards (in the US Clean Air Act) for the performance of technology still to be developed (emission of polluting gases by motor cars), were more successful.

The agenda-building function of Technology Assessment has been more prominent, especially since the late 1980s, and in relation to new and far-reaching technologies like biotechnology and information and communication technologies which could, or did, have legitimation problems (see for an example Van den Daele et al. 1997). For the "control" side of the two-track approach, this creates a somewhat ambivalent situation: is Technology Assessment only smoothing the introduction of new technologies, with minor or no changes, or does it actually make a difference?

4.2. Constructive Technology Assessment

Already in the mid 1980s (and starting in the Netherlands) a variant of Technology Assessment was developed which challenged the two-track approach by proposing to include Technology Assessment already in the design and development phase of new technology, specifically by broadening the aspects and the actors that were to be taken into account (IWTS 1984). This proposal to let Technology Assessment be part of the construction of technology was called Constructive Technology Assessment (Daey Ouwens et al. 1987; Smits and Leyten 1991). One implication was that other actors than governmental actors might play decisive roles, for example consumers (Fonk 1994) and producers themselves (Jelsma and Rip 1995).

Constructive TA is a way to overcome the so-called control and entrenchment dilemma (Collingridge 1980). The introduction of new technologies in society always also produces unforeseen effects, sometimes socially desirable (as when the telephone turned out to support social interaction and community building) and sometimes less so (as when the pesticide DDT induced resistance in the pests, and its residues caused environmental damage). Because most of these effects become manifest during and after introduction of a new technology into more general use, the possibilities for correcting them (if necessary) by adjusting the technology are limited. By the time the negative social impacts are recognised, technology is already firmly embedded in sectors, institutions, and practices. Thus, a dilemma between control and entrenchment.

There is no magic way out of the dilemma, but recent insights in the dynamics of technological development and social change show that it is not a message of despair either. The study of social shaping of technology (MacKenzie and Wajcman 1985) could be combined with the study of the social impacts of technology, seeing the two as aspects of a process of socio-technical change which might be called co-evolution (but not necessarily harmoniously) of technology and society. In this co-evolutionary or co-construction process, many actors are involved in making choices. For example, the choices made during the design process are not only influenced by the technical know-how of the designers but also by the chances of success of technologies to be developed as estimated by the planners, the managers, the sales departments, the investors etc. The properties of technology, its future impacts (including the distribution of risks and benefits) are shaped in interactions between the social actors. The shaping of technology, of its properties and impacts extends beyond the development stage into implementation, adoption and wider use. The composition of interacting social actors changes from one phase of the process to the other but each significant interaction leaves its imprints on technology and on the social environment. Technology and the social conditions co-evolve in the same movement (Rip and Kemp 1998), and assessments of various kinds occur all the time. The challenge is to prejudice these assessments in the right direction -- as part of an open-ended learning process about what the "right" direction could be.

For practical purposes, the key point is that the impacts of technology are prepared and shaped all along the process of development, implementation and use. This allows (and in fact requires) modified assessment strategies. To begin with, one can observe a marked shift in emphasis in Technology Assessment from general political-decision making processes to technological development, implementation and use. In order to minimise the socially undesirable impacts and to maximise the desirable ones, Contructive Technology Assessment includes activities to modulate the decentralised, multi-actor processes of development of technology. CTA therefore can be seen as a new design practice in which the assessment of impacts is being fed back into the development of technology in an iterative way and which contains an element of societal learning (Schot & Rip, 1997). There may still be an important role for the government and its agencies as initiators and as regulators of the modulation processes, but this role is not exclusive to government and can be taken up by other social actors.

One could argue that Constructive Technology Assessment is more effective than traditional Technology Assessment (early warning, policy-analysis) and the presently usual agenda-building Technology Assessment, because of its close involvement with technology, and at early stages. Its ambition is limited to modulating ongoing processes, however, and to be part of open-ended learning proceses. This is realistic, but not conclusive. The implication is that other varieties of Technology Assessment should complement Constructive Technology Assessment.

To position Constructive Technology Assessment further, three key characteristics can be specified which hold for all specific strategies and projects. First, to overcome the institutional separation of activities oriented towards promotion and control of technology, traditional control activities, i.e. anticipation of the future effects of technology and learning, should be integrated into promotional processes of technology development and introduction. This means that actors involved in control activities should actively participate in the technology design and development practices.

Second, in order to improve the quality of technology in society, the strong inward focus in processes of technology development and implementation (cf. Deuten, Rip and Jelsma 1997) should be avoided, or at least mitigated. In Constructive Technology Assessment, this is to be achieved by including more social actors as participants in interactions and by taking more aspects into account during the development and introduction of a new technology.

Third, the modulation process itself should display certain qualities. Because of irreducible uncertainties at the earlier stages, anticipation of impacts should be an ongoing activity. All the actors involved should be able to learn about the possible new linkages between the design options and the demands and preferences of the envisaged users. The learning should also include aspects of the political and social articulation of acceptability of technology in development and its linkages to broader cultural values of society. And finally, the actors should be reflexive about the processes of co-evolution of technology and society, of technology and its social impacts. (This listing is derived from Schot & Rip, 1997).

4.3. Generic strategies in Constructive TA

A number of generic Constructive Technology Assessment strategies have been identified. These strategies have not been tested experimentally, but natural cases have occurred which have been evaluated to show their feasibility and effect.

One generic strategy is known as technology forcing. It is the generalisation of technology forcing through government regulation (i.e., when technologies or other means to achieve the goals specified in the regulation are left to the actors to be developed): instead of traditional TA attempting to anticipate yet unknown impacts, here the desired impacts are specified beforehand and the technology is left open (to some extent, specification occurs, for example, through the recognition of promising options). The (desirable) impacts must be specified in an authoritative manner, either by a governmental regulation or by a broad agreement between large number of social actors. A time horizon may be set for accomplishing these impacts, and sanctions may be imposed on failure to achieve them, as happened with the US Clean Air Act (and led to politicking and strategic games, see the brief analysis in Rip, Van den Belt & Schwarz 1987). The basic idea is that technology actors are challenged to develop technologies that will fulfil the stipulated impacts. Although this strategy was taken up originally in government regulation, it can be applied by other actors.

A second generic CTA strategy is Strategic Niche Management. The concept itself was introduced to highlight an important aspect of successful introduction of new technologies (Rip 1992). As a Constructive Technology Assessment strategy, it emphasizes the quality of learning. Strategic Niche Management is the orchestration of the development and introduction of new technologies through a series of experimental settings or (technological) niches, which are temporary screened off from the working of selection mechanisms. Such settings are formed anyway around promising technological developments of which it is not known whether or not they will fulfill the expectations. In these experimental settings different categories of actors are brought together: the designers of technology, the envisaged future users, sometimes governmental agencies and if possible CTA agents who engage in facilitating and modulating the interactions between the first two categories of actors. In the interactions, various actors learn about the technical side of the design, about the needs and requirements of the users, about the cultural and political acceptability of technology in development. As designers of technology become aware of broader societal issues they are able to incorporate new aspects into the actual process of design and development. The contours of the institutional and technical context necessary for the new technology to function become visible and first steps in the process of embedding technology in society are made. Subsequently, graded introduction of the new technology is to be realised.

For our present purpose (which is quite limited; for some broader considerations see Box 5), it is important to note that the strategic niche management strategy, and other strategies that emphasize learning and reflexivity are productive in assuring quality control, but do not guarantee the nature and direction of the quality so controlled. The strategy of technology forcing, on the other hand, starts out by specifying the nature of the quality to be realized (and then runs the risk that the technology falls short). This then raises the question who can do such specification of quality in the face of conflicting interests; the "shadow of authority" is necessary to break through the impasses of zero-sum games (Kuhlman 1998a, 1998b).

This is not the place to discuss the broader and long-term issues involved in the macro-political aims of Constructive Technology Assessment (see Schot and Rip 1997). One interesting aspect deserves to be mentioned, however: Technology actors are prepared to become part-time CTA agents, especially if academic actors like ourselves are willing to participate and share responsibility. In each of these two cases, there are specific historical reasons for their being prepared to act as CTA agents. Behind thos specific reasons, one can see a willingness to take a longer-term view, often linked to prudential self-interest. In particular, maintaining one's position as a supplier appears to be an important driver. The action of oil companies in the 1960s to solve an environmental problem of synthetic detergents is a prime example (Daey Ouwens et al. 1987).

Should every actor become a CTA agent, and act accordingly while her own position remains recognizable? In such a world, no ISO standard would be necessary to assure the quality of the way we handle technology in society. In gender and development studies and activities, the notion that attention to gender becomes part of general development-oriented activities has been called 'mainstreaming' (Everts 1998). Similarly, the Technology Assessment philosophy and its Constructive Technology Assessment specification could become part of mainstream technology development, implementation and diffusion. Schot and Rip (1997) argue that the world should not become too harmonious: conflicting self-interests are incentives to articulate arguments and to learn, and thus to have better technology in a better society. They may well be right.

Box 5. The world according to Constructive TA ...

5. Risk repertoires and antagonistic coordination in industrial society

Where Constructive TA introduces reflection, learning and modest intentional design, at the meso- and macro-level of our industrial society emerging or pattern design occurs all the time. New and promising technologies are not born in a social vacuum. When entire domains of technological options are involved, as with nuclear fission and fusion, and now with genetic engineering and other forms of modern biotechnology, society responds to the promise, and to the uncertainties, of the unknown. In doing so it reflects patterns and attitudes available in its cultural repertoire, while also augmenting and changing these patterns.

Basing myself on Rip and Talma (1998), I shall describe some patterns in our present-day culture, themselves outcomes of earlier interactions, including experiences with new technologies. While learning occurs, there is no central instance to absorb the lessons and apply them. It is distributed learning, and in the case of new technology, often cast in an antagonistic mold. In this section, I will focus on the antagonistic patterns, and how they evolve (which includes their being modulated in practice). Whether one can systematically make such processes more tractable is a moot question; in section 5, I point out second-order or meta-level consderations.

5.1. Emergence of antagonistic patterns

How do antagonistic patterns around new technologies emerge? At first, there is recognition of novelty, and there are attempts to 'name' it. When radioactive waste was suggested as a possible weapon, it was called 'deathly sand.' The 'mushroom cloud' became the sign of the atom bomb. Such metaphors are one way of naming. Labels, like 'the atom,' around which actors can assemble, and with which they can link up, are the main route through which new technology acquires a social and cultural presence. Such labeling occurs at an early stage, before there is much experience with the new technology. But the label need not be very precise, nor need its contents be known and accepted, in order to connect different actors. Again, 'the atom' shows this well. The labeling may be contested, and shift after a time (as when 'atomic' became 'nuclear,' or when 'genetic engineering' became one of the defining characteristics of (modern) biotechnology). The process of naming sets the scene, creates associations, and shapes learning about the new technology. (It is fully equivalent to the micro-level naming that professionals do when they recognize the situation in which they have to design a building or a treatment as being like other, earlier situations. See further Schön 1983.)

Within the set of possible and actual linkages, there is a difference between those connected with the development and introduction of a new technology, and those which are not. Obviously, different interests are involved (even within the group of introductors there will be such differences). But one also sees a particular pattern emerge: a difference between insiders and outsiders. The introductors see themselves as insiders who know much more about the technology and therefore position themselves as also more knowledgeable about its potential embedding in society. At first, actors not involved in the new technology need not consider themselves excluded, or as being outsiders - but insiders will nevertheless define them as such. Such labeling by insiders, and associated behaviours, can in fact create coherent groups of commentators/critics which were not there before, as Albert de la Bruhèze (1992) has shown for the USA Atomic Energy Commission and radio-active waste disposal technology.

The combination of labeling and diffuse group formation leads to situations where stereotyping and inclusion/exclusion behaviour becomes self-reinforcing. Such situations are increasingly common, and this has given rise to a further, and reflexive, type of labeling, that of 'proponents' and 'opponents' of new technologies. Neither 'proponents' nor 'opponents' are simple categories, but to think in those terms seems natural. And the labels are used prospectively: introductors of new technology now expect that there may be contestation, and watch out for 'opponents.' The opponent/proponent dichotomy has become a pattern in our culture, and it serves actors in their attempts to order a complex environment. In that sense, the dichotomy is now a fact of life. (This goes so far that a whole secundary business has emerged around mediation and conflict-resolution, of attempts to increase acceptance of new technology, of public-opinion surveys and other monitoring exercises, and of training, on both sides, in strategies for effective contestation.)

The dichotomy of proponents and opponents is the strongest antagonistic pattern around new technologies. Its importance is related to longer-term features of of our societies, and is reinforced by recent developments. One such development is the increasing role of mass-media, and their need for dramatic story lines to draw attention; the storyline of proponents and opponents is one of the basic available narrative forms and will be taken up or projected immediately. Another development is the professionalisation of the environmental movement and other critical movements, so that there is personal and professional continuity of opponents across different technologies.

Other patterns occur, because concerns about one technology, and promises about the same or another technology, are not separate issues anymore. They are connected, for example through shared labels of 'risk' and 'promise' of technology. Or through referencing back: "Make sure that recombinant DNA technology will not suffer the same fate as nuclear technology."

Each particular case of introduction of new technology and of response, especially critical response, is embedded in broader patterns. Proponents of a particular technology ally themselves with the labels of 'progress' and 'modernity,' and opponents are forced to declare themselves against the presumption of modernity, or develop another view on progress. Introductors will foreground the promise of a new technology, and act to specify and realize the promise. They seek to overcome barriers against their project, and to label the hesitant and the doubtful as blind or irrational, and thus not deserving of serious consideration. Technological modernism gets articulated in this way. Others can speak for constituencies outside the charmed circle of technological modernism (including future generations and the environment) and in doing so will link up with the discourse of danger and risk. A recurring point is that the unknown may harbour danger (unknown but undesirable effects of novel technology), so that precautions are in order. Almost unavoidably, the value of existing, embedded, socio-technical order is emphasized and sometimes alternative non-technological options are outlined. Alliances are wrought in those terms, and the strong populist overtones create an uneasy mix of conservative-romantic reaction and alternative modernism. (See also Box 6.)

While the distinction between promotion and control, between proponents and opponents, is deeply embedded in our culture, and one can encounter typical proponents and typical opponents of technology as (often self-styled) spokespersons, the actual patterns and practices are more complex. The idea of intentional or emergent socio-cultural reduction of uncertainty about new technologies is the key to understanding these patterns. In

Looking back, one can see that a culture of concern and criticism about technology is visible from at least the late 19th century onwards, and probably earlier, if one takes the Luddites seriously. Such concerns are often related to the disturbing effects of new technology on existing social relations and societal patterns, and therefore labeled 'conservative' or 'romantic.' The 1960s and 1970s saw an important change, in the sense that technology criticism was adopted in the politically liberal/progressive repertoire. One effect was the articulation, in public debate, of technology (in general) as intrinsically linked with domination and control (of individuals, of groups, of countries). Another effect was that by the 1980s, substantial arguments by technology critics, no less than their simple political presence, had become regular inputs into government regulation. Introductors of technology expected concerns, at least concerns about risks, and began to take these into account in shaping the technology.
Such broad considerations have been taken up by Ulrich Beck and other sociologists in their analysis of the risk society. As Beck (1992) emphasizes, in present-day societies the distribution of risk has become as important as the distribution of wealth, and this links up with the emergence of a reflexive modernity. The term 'risk society' has become popular: it names, and thus locates, a diffuse phenomenon.

Box 6 A broad picture

applying this idea, I have focussed on the introductors, sometimes accepting the storyline about the heroic fights of technology's champions. This itself is a reduction of uncertainty. Rules, routines and regulation are other ways to do so. And there are socio-cultural patterns encompassing the routines, as well as the rules and regulations.

The emerging 'danger culture' of industrial society (Rip 1991) shapes daily life as well as influences regulation and control of technology. Think of the rules for our association with chemicals as an addition to the arsenal of cultural means of survival in industrial society. Rules like washing fruit, but also standards for maximum allowable concentrations of chemicals in the workplace and for acceptable daily intakes of food additives together form a net to catch and contain the dangers of chemicals. The rules may be justified in terms of toxicological data, but their effectivity is assured through the relevant cultural transformation (cf. my earlier emphasis on the dual, socio-cognitive, character of design).

The way we handle chemicals is embedded in a cultural transformation, covering a period of a century or more. The associated practices indicate something of how our kind of society handles potentially dangerous technologies in general. For example, they suggest that there is a concern about chemicals even when there is no actual sign of danger. This implies that there is diffuse political support for stringent measures: we spend resources and political energy to check for risks of chemicals, (including the risk of carcinogeneity, which is a social and political mobilizer) and devise systems to set adequate standards. Here, the cultural backdrop links up with, and reinforces, the structural distinction between promotion and regulation.

5.2. Risk repertoires and dominant images

Promises and risks of a new technology can be contrasted, and are, in fact, pitched against one another. In some cases, this gets framed by the proponent-opponent dichotomy to such an extent that it produces only grandiose declarations (as in the early days of the recombinant DNA controversy) and little learning. In other cases, weighing promises against risks leads to mutual articulation and a better understanding of the value of a new technology. Over time, repertoires of promise and risk have emerged which allow such articulation of the value of a technology - without necessarily producing a consensus. In particular, a socio-cultural pattern for addressing novel technologies has become established since the 1970s.

It is the issue of control, and partly the specific responses of the technology promotors to the possibility of control, that has shaped the risk repertoire characteristic of discussions, decision-making and practices since the early 1970s. The new risk repertoire was rooted in the novelty of the technology (and thus unpredictability of the dangers), and in the irreversibility and macro-character of the effects once they occurred (and thus in their essential 'unmanageability').

In the first half of the seventies, nuclear energy was the *topos par excellence* for playing out, and thus reinforcing, antagonistic interaction with respect to new technology. A repertoire became available, including ways of making risk arguments; roles were articulated and legitimated, with some professionalization of opponents *vis-à-vis* proponents, and with continuity of individual opponents across issues as one indicator. This culture and structure subsequently became the mould within which debate and action around the issue of recombinant DNA experiments were carried on. This research, a stepping stone to genetic engineering, emerged in the second half of the same decade, and has since become a second *topos*. To a certain extent, events were predictable. Promises would be voiced, and would be countered by articulation of risks.

Across the domains of nuclear and recombinant DNA technology, there was continuity in the type of risk conceived (runaway reactor/runaway organism, both with a potential for large-scale effects), in the type of arguments by which these risks were depicted as acceptable, and in the subsequent counter-arguments. Add to this the promise-requirement dynamics, where the claims about applications in medicine and agriculture shaped research agendas and venture capital interest in new R&D firms, and it is clear that a socio-cultural mould with a definite antagonistic component had become available. This pattern was visible in other domains as well. Siting of chemical plants became increasingly controversial, and probabilistic risk assessment criteria were applied to resolve the conflicts.

While biotechnology is now the overarching label, concerns and opposition are still focussed on genetic engineering - or, as is now common parlance among proponents, 'genetic modification.' Environmental release of genetically modified organisms, and the ethics of modifying animals have become the issues around which the basic struggle is being played out. While border crossings have become common, there still is something of a no man's land between the worlds of the modernist promotors of biotechnology and the concerned or merely reluctant receivers of biotechnology.

The patterns created by networks of labels and networks of actors aligned under such labels can be observed for other technologies. 'Nuclear' became a contaminated label in the 1980s; hence the acronym NMR, for Nuclear Magnetic Resonance, has been replaced by MRI, Magnetic Resonance Imaging - even if this usage of 'nuclear' had little to do with 'nuclear' power. A formula with chemical symbols is suspect, in spite of campaigns by the chemical industry. 'Natural' is a potent label, and actors will struggle to appropriate it for themselves. The antagonistic element in these socio-cultural patterns derives from the association with 'good' or 'bad', that certain labels carry, and that actors will want to capture, or avoid.

Positioning, and the battle of labels, has implications for evolving socio-technical orders. The impasse around nuclear power, and the attempts to create an inherently safe nuclear reactor, are one example. Labeling has become a down-to-earth issue in modern biotechnology, with the possibility of indicating on the labels of food products whether they contain genetically modified ingredients (or ingredients derived from genetically modified organisms) or not. The contrrast between North America and Europe is one factor (linked to the impossibility of distinguishing soy products from genetically modified origins or not), but also credibility dynamics. Industrialists had been resisting GM labeling, but now pride themselves (at least in the Netherlands) on doing so because it gives the individual consumer freedom of choice. Partly because of the uproar about GM food in the UK, early 1999, supermarket-chains led by Sainsbury (UK) have formed a consortium to produce GM-free brands. (The UK controversy is additionally interesting because it links up with issues of early warning (about risks of GM food) and responses, clamping down on the warning, in terms of ".. we all need to distingush good science from bad science", as it is phrased in a letter to the newspapers, 23 February 1999, signed by scientific luminaries.)

5.3. Implications

The working out of the danger culture is visible at the level of regulation. One example is the use of principles, like the pathogenicity principle, to reduce uncertainty in decision-making about the risks of genetically modified products. For production, rules of Good Manufacturing Practice, Good Industrial Large Scale Process and Good Development Practices, play a similar role: they are becoming routines for the actors within biotechnology, and are authorized at the political level. One could see this constellation of rules and division of labour as a mandate, although it is not organized by one single authoritative actor, as in the case of a standard-setting arrangement (Box 1).

While the gap between biotechnology and daily life is being bridged, in contrast to the yawning chasm in nuclear technology, there are still myths involved, *e.g.* the genetically modified organism as a 'monster' that has to be prevented at all costs. UK tabloids like *The Mirror* talk of "Frankenstein food," but this type of repertoire is pervasive, as when *The Daily Telegraph* (Feb. 17, 1999) opens its front page article with "Genetically modified crops could wipe out some of our most familiar farmland birds, plants and animals, according to a suppressed report written for the Government last year."

We are not implying that these myths should be done away with: culturally viable orders must contain myths. The question is whether the myths are productive myths. (Compare my earlier argument, in section 1, about tribal norms.) Practices, routines, and cultural legitimations become a coherent whole through myths. In occupational cultures of miners and of mountaineers, we see this in the way occupations define themselves as better, more courageous, and devoted to a high purpose, in order to manage and maintain their daily confrontation with danger. Similarly, in industrial society, the overall danger of living in such a society is backgrounded by paying close attention to standards for some chemicals, labeling of some foods. One can see this as creating safer practices while legitimating them through a myth of purity. While such a myth is productive, for a time, it can take on a life of its own and create rigidities -- and then has to be criticized and disconnected from standard setting, and in general, rule making and design of arrangements (Rip 1991)

At the moment, the myths of the runaway organism and of the 'monster' prevail, implying that counter-myths about harmlessness and beneficence will be ineffective. In the face of concern about genetically modified tomatoes or cheese, the counter-myth is: 'See, the tomatoes, or the cheese, are just like ordinary tomatoes or cheese (only better, or cheaper, or both).' The monster is declared to be harmless, even friendly. Whether this is actually the case or not, the point is that cultural patterns like myths do not change simply through declarations. However, they *do* change, but through evolving practices and domestication of the new technology. The debate, in the 1950s and 1960s, about the advent of the computer as the new tyrant -- or the new slave -- (Van Oost 1994), has died down, and with a PC in every home and on every office desk (and perhaps a notebook on everyone's lap), it will not flare up again.

Risk has become the accepted criterion for discussion and implementation of control of new technologies, but for other features there is no articulated socio-cultural pattern. For information and communication technologies, one can think of the ambivalence of jobless growth, and other effects of delegation to intelligent machines. For modern biotechnology, a discussion is just getting off the ground whether new products should also be assessed in terms of their societal value. The fact that it is called 'the fourth hurdle' indicates the extent to which it is seen by proponents at least, as part of their heroic storyline of a battle agains opponents.

6. In conclusion

Having looked at the socio-cognitive dynamics of science, scientific controversies and scientific expertise (section 1), having presented Technology Assessment and in particular, strategies for Constructive TA which emphasize intelligent trial & learning (section 3), and then gone on to a broader, societal canvas to sketch cultural patterns shaping risk discourses and controversies about new technology (section 4), are there some general elements, perhaps even conclusions? The key point was set out already in the introduction, when I suggested that intractable problems become somewhat tractable in practice, and that it is important to understand the how and why of such patterns of creating and maintaining tractability. One reason is to be able to reflect on the quality of the processes and outcomes, and if necessary, to shift or at least modulate the practices. The other reason is the need to design better arrangements, rules, perhaps even institutions, and to locate proposals, as for a precautionary principle, in such a design perspective (section 2).

What I need to do in this final section is to draw together the understanding of the how & why of creating and maintaining tractability, and consider possibilities of turning such insights in how things go into suggestions, advice or even guidelines how to do things intentionally. Of necessity, I will remain rather global, but further specification to concrete approaches is possible (it does require extra work).

Clearly, process is very important, with ongoing trials and repair work, and structured by substantial as well as "tribal" rules and frames (up to the action potential of cultural myths). Substantial and tribal are two sides of one coin, often mixed up inextricably. One can try to extricate them, say by separating "facts" from "values" and "interests." This may be useful in particular cases, but cannot be a general solution. A general guideline would be "dual design," that is, is design (intentional as well as emergent) both sides of the coin have to get attention. Tribal norms, for example, even if manifestly biased, may be important to keep the overall system going. In other words, there is a system-level goal: not just of survival, but of productive survival. As I noted before, productivity cannot be defined a priori, but its articulation is part of the process of creating tractability.

A key step in tractability processes turns out to be temporary closure, whether epistemic as when a paradigm or dominant problem definition (or dominant design) closes off foundational debates, or social, as when participation is restricted to those with standing (because of their expertise, their being stakeholders, their being powerful -- the criteria vary, but there is some rstriction). A typology of risk situations can also create closure, if it is accepted as comprehensive and there are practical guidelines or procedures to allocate concrete and messy situations to one type or another.

The closure I consider here relates to two-tier phenomena (or processes), where an overarching or foundational "tier" is black-boxed so as to make ongoing work, action and interaction possible in the other "tier." If the black-boxing becomes absolute, the overall processes lose flexibility, and their capacity to respond productively to the unexpected. Thus, there are good reasons to recognize the existence of two tiers, and the preliminary or contingent nature of the closure.

Note that the (temporary) closure has cognitive as well as social components. This is brought out nicely in the phrase "serviceable truth", coined by Jasanoff (1990, p. 250) as a truth which "satisfies tests of scientific acceptability and supports reasoned decision-making." The phrase is now taken up and applied in concrete cases by political scientists like Rob Hoppe and David Guston. It can refer to specific knowledge claims or pieces of research, but it also indicates a certain pargamtic orientation of science and its relation to policy and decision making, which may give rise to sustained work in 'regulatory science' (Jasanoff) or 'post-normal science' (Ravetz). This is, effectively, dynamic closure in a two-tier situation, including a certain division of labour in which the new professionals and their quality control through extended peer review have to balance the different claims made upon them.

There is also horizontal closure, for example of access (of actors and viewpoints) and of scope (of problem definition). Often, the two are mixed. In controversies, for example, actors may want to expand the scope in order to get a better hearing for their arguments (e.g. general health issues in cancer controversies, evolutionary considerations in GMO controversies), but in doing so the arena is expanded, and new actors participate who may shift the balance in unexpected directions (Petersen and Markle 1981).

One example of horizontal closure is the creation of dichotomies and giving unconditional preference to the one side above the other. Facts, rather than values; rationality rather than emotions; experts rather than laymen; purity rather than messiness; precaution rather than trial and error; etc. If distinction plus preference become absolute, one gets imprisoned in a dichotomy trap. To get out of such a trap, the grey transitional zones have to be seen as interesting in their own right, rather than complexities that have to be cleared up. Multi-criteria analyses are important to introduce further categories, so that the dichotomy trap will be transcended. If they insist on clear and mutually exclusive dimensions or categories, however, they will fall into the polychotomy trap: the illusion that clear distinctions are an absolute goal, rather than a practical compromise to be assessed according to the purposes at hand.

Recognizing the plurality and messiness of situations (and of life, and the universe, and everything) one can try to have closure recognized as always preliminary. With the advent of modern information and communication technology, interactions with many and variegated inputs are possible and some convergence can be achieved, not as a consensus, but as productive interaction between positions and stories. The phrase 'k-aleidoscopic closure' captures this possibility, and Murray (1998) shows how it can be implemented in cyberspace. There are quite a number of experimental projects, exploring the possibilities of information and communication technology for deliberation and convergence. But the excitement about the new technological possibilities should not let us forget the principle problems involved: how to include justification to outside audiences into the process and still keep it convergent? And in general, how to overcome the intra-murality trap: what has become tractable within the confines of the conference centre or the computer-supported experiment need not solve intractibility in the wider and messier world. One needs kaleidoscopic closure in the real world, rather than in an artificial and protected setting.

The intra-murality trap was very visible in the participatory TA exercise on the introduction of genetically modified plants in the environment, organized by the *Wissenschaftszentrum* in Berlin (Van den Daele, Pühler and Sukopp 1997). While the structured discussions were productive, the environmental groups decided, at one moment, to step out so as to avoid having the eventual conclusions being attributed also to them, which would hamper their freedom of action in the wider world. In pursuing their own interests in this way, they also (inadvertently or intentionally) undermined the legitimity of the exercise, which was based on getting the contending parties together.

Thus, the basic design principle of intra-mural exercises: capture the variety out there, and especially, get the main contenders together and interacting, carries in itself the seeds of failure. An intriguing example is how a meeting on the risks of a herbicide in the US in 1973 became a consensus conference by accident -- and turned out to be productive --, but when it was designed as such in 1979, environmental groups refused to participate, and the conference failed to achieve its purpose (Rip 1986).

The intra-murality trap is particularly salient in specially designed exercises, which try to contain the agonistic and antagonistic interactions in a limited space-time frame. But the phenomenon is not limited to such exercises. Schwarz and Thompson (1990) in general, and in a slightly different way Hoppe and Peterse (1998) who analyse a debate on airport siting, suggest that all three main types identified by cultural theory (entrepreneurs, hierarchists and collectivists) have to be present and get a voice, in order that the process reflects the variety and contentions, and an eventual convergence will not be broken up later on. Still, strategic action will occur because the different types will have different preferences for the various outcomes.

The alternative approach implicit in my discussion of learning in antagonistc situations is to go with such processes and grasp opportunities for improval, rather than design a "good" process as such. In other words, quality assurance of the process becomes more important than the better blueprint at the beginning.

Antagonistic interaction is one variant of a wider range of what one can call 'agonistic' interaction: struggles, contrasts, tensions and difficult assessments, but also complementarities and recognition of the roles of the different parties (and aspects of new technology). Socio-cultural patterns orient actors, enabling them to reduce the uncertainties introduced by new technologies. I emphasized the antagonistic component in these patterns and have argued that these are more than circumstantial, or only a reflection of the general conflictual nature of society. They are part and parcel of societal reduction of uncertainty. It is the way in which society learns to handle new technology (and itself).

Present-day quality assurance systems rely on the specification of processes and their documentation, rather than the outcomes. This assumes that it is known, and generally accepted, what quality consists in, and that the actors and organizations involved are known. What about quality control in non-institutionalized settings, where new technology is being developed and effects are not yet known? The 'control' part of quality control has difficulty accommodating change, novelty, unexpectedness. Constructive Technology Assessment trajectories emphasize open-ended learning, and may thus be a model for quality control in emerging, non-institutionalized situations.

One could argue that such a quality assurance system again carries the seeds of its own failure: as soon as it has been put up, actors will use it to further their own purposes rather than let it produce overall quality. In practice, this can be made more difficult (for example, through sanctions and diffuse credibility pressures). In addition, actors (quality assurers or others) can do repair work; in fact, a quality assurance system can only work, i.e. be somewhat productive, if there is space for repair work.

One additional tension inherent in this approach should be mentioned. In emphasizing quality assurance and the eventual goal of better technology in a better society, other considerations, in particular issues of democracy and justice, are backgrounded. At a minimal level, the requirement of transparancy, important in a democracy (Van den Daele, Pühler and Sukopp 1997, p. 90), may not always be conducive to productive negotiation. More generally, broad participation, while perhaps a "right," is not a productive way to encompass variety. Van den Daele, who has beem confronted with these issues repeatedly, suggests that the multiplication of viewpoints (as a result of increased participation) will make the achievement of an integrated result and formulation of concrete policies more difficult. This could lead to a return to formal democratic policy and decision making procedures, unless civic society itself is able to achieve such integration (Van den Daele and Neidhart 1996, p. 14). Clearly, this will not come about by itself.

As I have sketched the reflexive co-evolution of technology and society (especially in section 4), dominant patterns, and thus dominant designs, emerge which allow for such integration. The proponent-opponent dichotomy and the risk discourse which emerged in the 1960s and 1970s is one example of such a dominant *de facto* design. One may have one's doubts as to its productivity, especially in the face of the new technologies and the new circumstances of the 1990s, but it is definitely a solution to Van den Daele's concern.

What could be (and become) a dominant design better suited to the times and technologies? It must always produce kaleidoscopic integration, without doing away with antagonisms and outlyers. It must relate to ongoing societal dynamics: to have an ideal approach which does not work because it does not fit the tribal norms is of little purpose. These are general design requirements. As an approach to discovering what such a design could be, I suggest to explore, in analysis and in practice, issues of new risks and new responsibilities as two sides of one coin.

As in a serial, I will leave the reader with this "cliffhanger," looking out for the sequel.

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ON THE ROLE OF DECISION ANALYTIC MODELLING

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Contents

1. EXECUTIVE SUMMARY

In this paper, we consider the use of decision analytic modelling as a vehicle for supporting the management of technological risks, with an emphasis on settings where the application of the precautionary principle seems warranted. We also clarify related concepts - such as resilience, adaptability and flexibility - and argue that in the absence of scientific evidence, it may be appropriate to conduct the analysis at the level of strategic qualitative factors of this kind. The key conclusion from this paper is that decision analytic models hold considerable potential, as their construction 1) enforces a systematic appraisal of the risks involved and 2) communicates the implications of incomplete knowledge about scientific facts or the stakeholders' value concerns. This notwithstanding, these models are subject to the same fundamental limitations that apply to any formal modelling endeavour in the presence of considerable uncertainties.

2. INTRODUCTION

Scientific and technological progress continues to reshape our societies at a pace that is unparalleled in history. In many respects, this progress has changed our living conditions for the better; but on the other hand, it has also given rise to harmful environmental consequences that threaten prospects for sustained development.

In the presence of considerable scientific and technological uncertainties, it is often difficult to determine what the potentially harmful consequences are, or what causal relationships link them to human action[199]. This, in turn, implies that the assumptions of traditional risk analyses – which presume well-defined relationships between hazards and harms – no longer hold, wherefore these analyses are not of much avail when uncertainties and stakes are high [200]. In response to the challenges posed by such decision contexts, the precautionary principle has been heralded as a guideline for responsible action. While open questions remain as to the details of its implementation, the principle itself is based on the sober realisation that limits to available scientific knowledge should be recognised in the shaping of regulatory policies[201].

In what follows, issues related to the implementation of the precautionary principle will be discussed from the perspective of formal decision analytic modelling. For the consideration of the social and institutional dimensions, we refer to the other field papers produced in this project and to the guidelines that have recently been developed to support practitioners[202] .

3. DECISION ANALYSIS

The theoretical foundations of decision analysis can be traced back to the seminal works on utility theory[203] and, somewhat more broadly, to the theories of preference measurement[204]. In the late 1960s, decision analysis became a discipline of its own, and over the past few decades, it has grown into a mature scientific field with applications across a broad range of domains. Resource planning, siting of hazardous facilities, assessment of environmental risks and the shaping of regulatory policies are but a few examples of the types of problems that have benefited from formal decision analytic modelling[205]. At present , decision

[199] Hey (1991), Dovers and Handmer (1995), Wynne (1992), Gray and Bewers (1996), Walker (1998).

[200] Funtowizc and Ravetz (1990), Stirling (1998).

[201] Cf. O'Riordan and Cameron (1995), Rogers (1998)

[202] See, e.g., Deville and Harding (1997).

[203] See, e.g., von Neumann and Morgenstern (1947).

[204] See, e.g. Krantz et al. (1971).

[205] See, e.g., Corner and Kirkwood (1991).

analysis offers a range of systematic methodologies for the modelling and clarification of decision problems characterised by uncertainties, multiple alternatives and conflicting objectives[206].

Fundamentally, decision analysis is about the application of formalised rationality to complex problems in such a way that the key elements in the decision - objectives, alternatives, and uncertainties - are explicitly defined. This approach is conducive to a more responsible, transparent and democratically defensible decision process, which in itself is an important benefit quite apart from the outcome of the process. For introductions to decision analysis, we refer to the works of Bunn (1984), French (1986) and, von Winterfeldt and Edwards (1986).

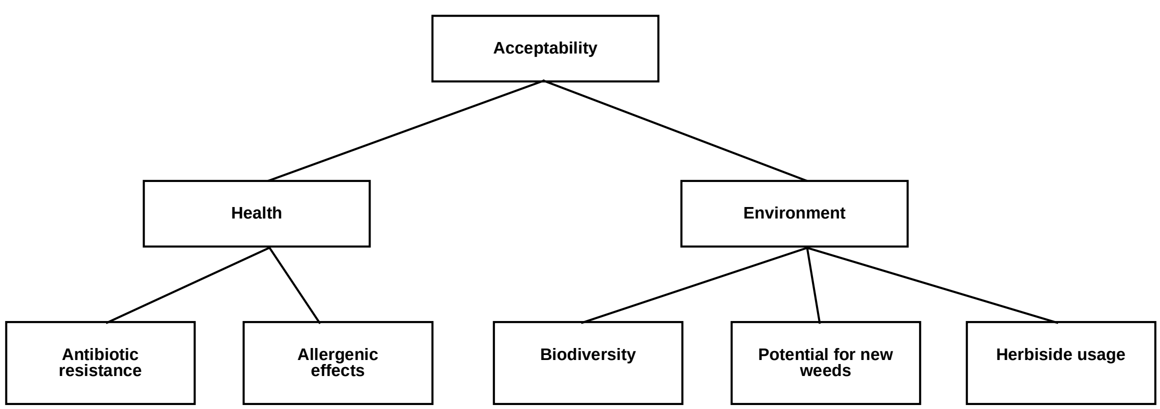
In this section, we illustrate decision analytic models in the light of two commonly applied approaches, i.e., value trees and decision trees. This is by no means intended to imply that other approaches would be irrelevant or that environmental problems would not call for more elaborate modelling[i]. Rather, these two approaches exemplify typical properties of decision analytic modelling and, in particular, allow us to consider how current modelling approaches might be extended to accommodate scientific uncertainties, thus paving way for the operationalisation of the precautionary principle.

3.1 VALUE TREES

In value trees, the stakeholders' value concerns are structured in the form of a tree where the higher level elements correspond to generic, overall objectives and the elements at the lowest level correspond to attributes that are relevant for assessing the attainment of these objectives.

For example, the tree in Figure 1 shows a value tree that captures a few of the concerns related to the release of GMOs into the environment[207]. Here, "health" and "environment" denote general objectives, while allergenic effects and the potential for increased resistance to antibiotics denote attributes that are relevant to the consideration of health effects. Despite its simplicity, the value tree is useful in that a distinction between scientific evidence and value judgements is made. That is, scientific evidence about allergenic effects of GMOs bears on the measurement of these effects with respect to the attribute "allergenic effects", while value judgements about the importance of "health" and "environment" are captured by the weights that are assigned to these attributes.

Figure 1: A Value Tree Illustrating Concerns Related to the Release of GMOs into the Environment



[206] Cf. Bunn (1984).

[207] A more extensive characterisation of such concerns is given by Stirling and Mayer (1999).

Value trees are best suited for the analysis of problems where several incommensurate objectives – as portrayed by the attributes in the value tree – must be accounted for. Specifically, value tree analysis presumes that 1) the alternatives' consequences with respect to the relevant attributes can be characterised and translated into attribute-specific values, and 2) the relative importance of attributes can be captured through a set of weights. Once the alternatives' attribute-specific values and attributes' weights have been elicited, support for the identification of preferred alternatives can be provided by computing the overall value of each alternative as the weighted sum of its attribute-specific values.

The following observations apply to value tree analysis in the presence of large scientific and technological uncertainties:

1. Uncertainties are not explicitly modelled. This deficiency, however, is not a prohibitive one, provided that sensitivity analyses are conducted to explore the range of possibilities that are related to 1) scientific evidence, as measured by consequences with regard to lowest-level attributes and 2) value concerns, as measured by the attribute weights.
2. Value tree analysis presumes that relevant concerns can be structured into a commonly accepted framework using either available sources of information (such as official guidelines or survey articles[208]) or participatory processes (such as consensus conferences; see Durant and Joss 1995). Yet, in the presence of scientific and technological uncertainties, there is a possibility that totally unforeseen concerns emerge which are not captured by the models thus constructed.
3. From a theoretical perspective, the use of additive value representations for normative decision support is warranted only under rather stringent assumptions about the structure of the stakeholders' preferences. This notwithstanding, additive representations can be used as plausible approximations even if the stakeholders' preferences do not fulfil the underlying assumptions (e.g., to some stakeholders, economic concerns may matter only on condition that environmental harms remain acceptable).
4. Value trees are static representations which are best suited for the analysis of single-stage decisions. They are not good at capturing causal relationships that are crucial to the understanding of dynamic decision processes: contingencies between successive decisions are hard to convey in the value tree framework.
5. When several stakeholders' interests are involved, the common value tree representation may - under certain assumptions[209] - be used to aggregate the stakeholders' views into a composite value representation (i.e., social welfare function). In practice, however, the construction of an aggregate representation involves both theoretical and practical difficulties associated with the assignment of weights to the stakeholders.

Apart from normative applications, value tree analysis may also be employed as a tool for supporting communication and interaction between stakeholders in their search for a consensual settlement [210]. Here, the motivation for the construction of value trees stems from the realisation that the explication of value concerns – which are crucial in risk management – is supportive of an open and more defensible decision process [211].

3.2 DECISION TREES

Decision trees illustrate relationships between successive decisions and chance events by portraying the decision problem as a sequence of decision nodes and chance nodes. Each decision node corresponds to a choice among a discrete set of options (e.g., authorisation permitted or denied), while chance nodes depict

[208] See Ockhuizen et al. (1996), Rissler and Mellon (1996), Snow and Palma (1997), Salo et al. (1998).

[209] Keeney and Kirkwood (1975).

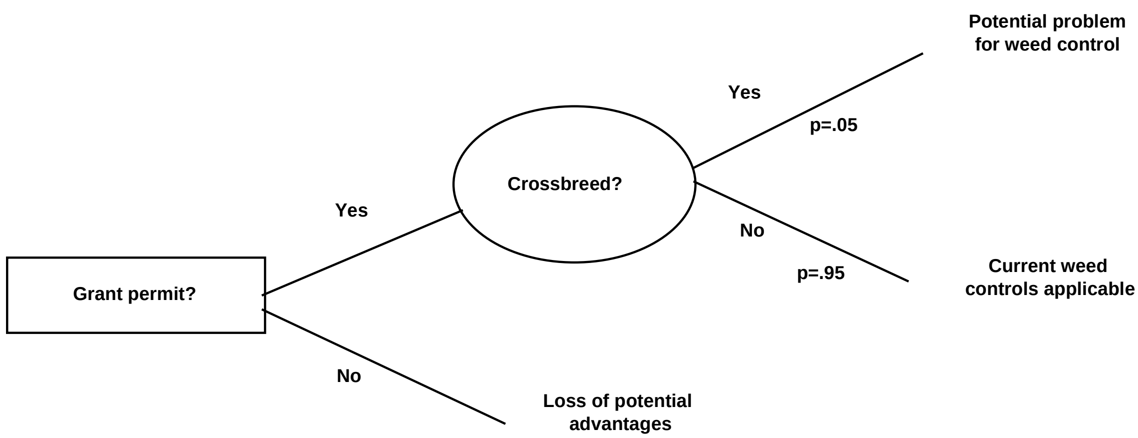
[210] Hämäläinen et al. (1992).

[211] See also Stirling (1997), Stirling and Mayer (1999).

unknown events which are relevant to the outcome of the decision process (e.g., it is possible that a plant crossbreeds with its wild relatives). The sequences of decision nodes and chance notes terminate at end nodes which characterise final outcomes and are of greater or lesser utility to the stakeholders (see Figure 2). The decision tree is solved by recursion from the end nodes towards the first node so that at each decision node, the option with the greatest expected utility is chosen[212].

An advantage of decision trees is that – unlike value trees – they can be used to analyse decisions that are contingent on earlier choices and chance events. Such contingencies arise, for example, when the permission to deploy technology is granted under restrictive conditions which depend on the outcomes of subsequent environmental monitoring. The recognition and analysis of such contingencies is crucial for instance in the development of regulatory policies that are intended to provide insurance against unfavourable outcomes[213].

Figure 2: A Decision Tree with a Possible Sequence of Decisions and Events



The following limitations need to be recognised in employing decision trees for risk management:

1. The construction of decision trees presumes that the order of the events and decisions can be anticipated; i.e., decision trees are not flexible in terms of capturing uncertainties which relate to the *temporal structure* of the problem.
2. The full specification of decision trees assumes that the outcomes of chance nodes are known and that the probabilities of these outcomes (which are assumed to be exhaustive and mutually exclusive) are known as well. In the presence of scientific and technological uncertainties, these assumptions may not hold because of difficulties of defining outcomes and their probabilities with sufficient confidence (cf. Bescher 1983). Extensive sensitivity analyses can reveal the implications of changes in the numeric parameters; but errors of omission due to missing outcomes cannot be accounted for in this way.
3. Decision tree modelling lays less emphasis on the stakeholders’ concerns than the construction of value trees. In practice, value concerns can be addressed by employing value trees in the evaluation of end nodes[ii].
4. The definition of end nodes presumes that all later developments can be synthesised into a single node which is then evaluated. In regulatory contexts, the setting of such a time horizon may be difficult, particularly when temporal dimensions such as persistency, irreversibility and delay effects are crucial.

[212] See, e.g., Kirkwood (1997).

[213] Cf. Costanza and Cornwell (1992).

While decision trees are typically constructed for normative decision support, they may also be deployed for more qualitative purposes, e.g., in order to illustrate how *scenarios* come about through sequences of consecutive decisions and events[214]. Thus, as in the case of value trees, the possible uses of decision trees need to be conceived broadly, whereby their role in communication support may be appreciable.

3.3. COST-BENEFIT ANALYSIS

The various variants of cost-benefit analysis typically 1) convert the future costs and benefits of new technology into monetary streams and 2) provide decision criteria – such as cost-benefit ratio, payback period, and return on investment – for the comparison of these streams.[215]

Thus, cost-benefit analysis is premised on the assumption that the relevant impacts of technology can be aggregated into monetary terms and that the consideration of monetary impacts provides a sufficient basis for decisions. In this sense, cost-benefit analysis can be regarded as a simplified multi-criteria approach where money is employed as the unit of aggregation. This may be reasonable in the corporate world where companies strive to improve their economic competitiveness by using cost-benefit analysis as a systematic framework for the comparison of investment opportunities.

In regulatory contexts, however, the application of cost-benefit analysis may be fraught with difficulty. The following observations point to pitfalls in applying cost-benefit analysis for the operationalisation of the precautionary principle:

1. The aggregation of economic, societal and environmental impacts into streams of monetary benefits and costs presumes that 1) these impacts can be anticipated with some accuracy and that 2) there exists a defensible procedure for translating these impacts into monetary terms. From the methodological perspective, both assumptions are questionable: on one hand, new technologies have repeatedly given rise to consequences which were not foreseen when the technologies where introduced; on the other hand, the conversion of these consequences into monetary terms is a matter of *values* rather than that of merely choosing a technical parameter (i.e., the choice of any one conversion rate may favour one stakeholder group more than some other).
2. The future streams of costs and benefits depend on how the problem boundaries are set. In principle, more comprehensive results can be obtained by extending the boundaries of the analysis, although such an approach is likely to complicate the assessment task because even greater uncertainties must be accounted for.
3. The consideration of temporal preferences (as effected through the adoption of discount rates) involves far-reaching value judgements the ramifications of which are easily buried into the details of technical analysis. For example, how should the costs that incur to future generations be weighed against short-term benefits?

To sum up, the following deficiencies detract from the usefulness of cost-benefit analysis as a methodology for the operationalisation of the precautionary principle:

1. In regulatory settings, decisions are often less concerned with monetary impacts than with the recognition of issues that matter to the public most (e.g., potential harm to human health or the environment). The conversion of the anticipated impacts into monetary terms is therefore misplaced in that the decisions are largely shaped by other concerns, anyway.
2. The deployment of controversial technologies involves incommensurate dimensions which, in view of the tensions of the policy process, can rarely be positioned on a common scale. Any such positioning will involve deep-searching assumptions (e.g., what is the value of human life?) that may be hard to discuss or harmonise across different domains of jurisdiction.

[214] See, e.g., Bunn and Salo (1993).

[215] Pearce and Markandya (1989).

3. The mapping of various concerns into a single dimension through embedded parameters renders the results of cost-benefit analysis less transparent than other analyses where the separate dimensions are retained (cf. multi-criteria decision analysis).

4. As noted above, the conversion of expected monetary streams into the present involves value judgements about how the future costs and benefits should be compared with present ones. This, again, is highly problematic.

In view these observations, it appears that the decision analytic framework – and value trees in particular – offer a broader framework for the explication of societal, economic and environmental impacts. One of the reasons for this is that multi-criteria decision analysis tends to place less emphasis on the "solution" and gives more attention to the elaboration of scientific knowledge in relation to the stakeholders' value concerns.

In the context of the present project, some of the relevant questions include how the decision analytic representations might be adapted to account for scientific uncertainties. A starting point for such a consideration can be set by 1) explicating the different types of uncertainties that need to be accounted for and 2) investigating how modelling approaches might be extended in response to these uncertainties.

4. DIMENSIONS OF UNCERTAINTY

In addressing the operationalisation of the precautionary principle, it is helpful to distinguish between different qualitative types of uncertainties[216]. For example, distinctions between ignorance, indeterminacy and uncertainty can be made on the basis of 1) the abilities to define the relevant phenomena comprehensively and 2) the theoretical and practical means of acquiring information about these phenomena.

It is also useful to consider what parts of the analysis are affected by "uncertainties". For example, uncertainties may bear on:

1. The scientific knowledge on which risk assessment/analysis depends.
2. The stakeholders' value judgements on the consequences of new technology.
3. The range, efficacy and effectiveness of the available policy measures.

The questions below highlight some of the issues related to these dimensions:

Table 1: Examples of Dimensions Related to the Implementation of the Precautionary Principle

Physical causation	❍ Causes – What particular characteristics of the technology are potentially harmful? ❍ Consequences – What harmful effects can the introduction of technology have? ❍ Causation – What causal relationships govern the emergence of harmful consequences? ❍ Conditions – Under what specific external circumstances may the harmful consequences come about? ❍ Detection – What means are available for detecting and monitoring the harms? ❍ Time of manifestation – When might the harm come about?
Value concerns	❍ Stakeholders –Who are the stakeholders that may be affected by the harm? ❍ Communication – Do the stakeholders have sufficient, impartial and intelligible information about the technology? ❍ Preferences – Do the stakeholders have stable preferences and are they willing to explicate them? ❍ Representation - What deficiencies are associated with the mechanisms of representation through which the stakeholders' views are brought into the policy discourse?

[216] See, e.g., Wynne (1992), Smithson (1989).

Policy response	❍ Measures – What policy measures could be instituted to counter the harm? ❍ Effectiveness – How effective are these measures?

While much of the debate on the precautionary principle has revolved around scientific uncertainties (i.e., physical causation, such as impacts of GMOs on the ecosystem), it seems that these uncertainties trigger hesitation in other areas as well. For instance, when people were questioned about their views on synthetically constructed genes, they gave mixed and baffled responses. Presumably they did so because the whole notion of "artificial life" in this sense transcends prevailing notions of what modern science is capable of and what ethical implications of these capabilities have[217]. From the perspective of implementing the precautionary principle, this implies that it is necessary to pay attention to how the incompleteness of scientific knowledge affects value judgements. Specifically, the larger the scientific uncertainties, the more attention should be given to negotiation and democratic debate as opposed to the reliance on formal modelling approaches alone[218].

5. METHODOLOGICAL EXTENSIONS

Traditional decision analyses are typically based on the construction of a complete preference model. Such a model includes 1) a full description of anticipated consequences with respect to the relevant attributes and 2) an elaboration of the decision makers' value concerns, as expressed by the attri bute weights. Once the preference model has been constructed, it is then subjected to sensitivity analyses, in order to determine how sensitive the results are to changes in knowledge about the potential consequences, on one hand, and changes in stakeholders' values, on the other hand.

Current research in multi-criteria decision analysis, however, has recognised that significant insights may be gained from an incomplete model specification. Motivated by this realisation, several methods have been developed to support the analysis of problems for which the construction of a complete model is either exceedingly difficult or even unnecessary. The rationale for these methods, therefore, is to reduce the information requirements of the analysis while making the most of the information that can be obtained. Examples of these methods include the work of Moskowitz et al. (1989), Hazen (1985), Weber (1985, 1987), Salo and Hämäläinen (1992, 2001) and Salo (1995). Gradually, the use of multi-attribute methods with partial information is gaining recognition in the field of risk management as well (Kadvany 1995).

A particular advantage of the above methods is that they distinguish between different types of uncertainties:

- The recognition of *scientific uncertainties* at the level of assessing regulatory options with respect to their consequences on the attributes.
- Uncertainties related to the *value concerns* at the level of assessing the relative importance of attributes.

Furthermore, these methods seem particularly promising in the area of group decision support, because they serve to highlight similarities and differences between the stakeholders' viewpoints [219].

Since the development of multi-criteria methods for dealing with partial information has been driven by the difficulties of developing a complete model specification, these methods are of immediate relevance to the operationalisation of the precautionary principle.

[217] HMSO (1993).

[218] Cf. Funtowicz and Ravetz (1990), Levidow (1998), Levidow et al. (1996a).

[219] Hämäläinen et al. (1992).

5.1 OPERATIONALISING THE PRINCIPLE

We next present some suggestions as to how decision analytic modelling might be harnessed for the operationalisation of the precautionary principle. We also refer to the work of Deville and Harding (1997) who consider how institutional responsibilities, communication policies and processes for accommodating scientific evidence might be shaped to align operational practices with the precautionary principle.

Conceptually, one can distinguish between:

1. Formal analysis, i.e., the ways in which scientific information and knowledge about the stakeholders' value positions are managed from the modelling perspective.
2. Interactive processes, i.e., the interactions and deliberations through which the different stakeholders contribute to the analysis and take part of its results.

In practice, formal analysis and interactive decision processes are closely related and even inextricably linked. Here, apart from the normative implications that are accorded to formal analysis, a significant benefit of decision analytic modelling is its ability to *inform* the stakeholders, as the transparent explication of scientific evidence and stakeholders' value concerns helps to convey the essentials of the problem. In this regard, decision analysis differs from the more technically oriented variants of cost-benefit analysis in that its objective is not to offer 'analytical fixes' but, rather, to lend more structure and manageability to the decision processes.

Since decision analytic modelling may have several different uses, the types of models that are built should be aligned with the specific objectives and expectations that are placed on the modelling endeavour. It may be advantageous to construct different models that are geared towards different uses: an examination of gaps and overlaps between alternative problem formulations helps in studying how the results depend on the type of the modelling approach.

While decision analyses are often conducted in order to assess pre-defined, known options, the models can also be used to shape options which comply with the constraints imposed by economic, environmental and social concerns. Here, there are considerable synergies between decision analytic modelling and constructive technology assessment (CTA) which seeks to engender a greater awareness of societal requirements within the developer community[220].

5.2 FORMAL ANALYSIS

In terms of the modelling approach, the following guidelines seem to be aligned with the operationalisation of the precautionary principle:

1. Where scientific evidence is scarce or uncertain, examine ranges of parameter values to explore what implications possible perturbations have on the results.
2. When evaluating potential consequences with respect to attributes of concern, employ several value (utility) functions to cover a range of values that may be associated with the anticipated consequences.
3. In assigning weights to the attributes, involve all the relevant stakeholders, carry out sensitivity analyses and ensure that the weights are clearly communicated and understood.

At the level of analytical tools, the methods developed for the processing of partial information hold potential in the operationalisation of the precautionary principle. The following arguments, among others, support their use:

[220] See, e.g., Merkhofer (1982), Schot and Rip (1996).

1. These methods have been developed to support analyses of problems where complete information is either impossible or too costly to obtain. Thus, by construction, they are applicable to problems where uncertainties are substantial.

2. In these methods, the results become gradually more informative, i.e., dominated options can be gradually eliminated as more knowledge is obtained. In this way, the analysis converges towards the identification of the nondominated options while in traditional analysis the 'best' option is first identified and only then subjected to sensitivity analyses. Here, a drawback in traditional analysis is that it may become anchored to the option that, based on the early steps, appears to be the best one. It may be difficult to let go of such an option once the expectations have become focused on it.

3. During the intermediate phases of the analysis, it is possible to examine what impact any further information would have on the results. That is, one can analyse to what extent it *pays off* to spend further time and effort in searching for more information.

4. These methods can also be seen as means of performing *simultaneous* sensitivity analyses with regard to all the parameters. If no option emerges as the best one, alternative decision criteria (such as maximin, minimax regret; see Bunn 1984) can be applied to derive suggestions about the options that outperform others. This is in contrast with traditional sensitivity analyses where only few parameters are examined at a time.

5.3 INTERACTIVE PROCESSES

Interactive processes refer primarily to the activities involved in the capture of the stakeholders' value concerns and the deployment of decision analytic representations in support of discussions and deliberation. Here, the following guidelines seem to be aligned with the operationalisation of the precautionary principle:

1. Identify the stakeholders and explicate what harms the technology might bring to them.
2. Engage the stakeholders into an open discussion about the possible harms and remain open about scientific uncertainties[221]
3. Wherever possible, submit the results of analysis to an extensive peer review and solicit critical comments from a wide audience.
4. Carry out sensitivity analyses to support communication. Recognise that in situations where the precautionary principle is called for, the results of the analysis cannot be regarded with the same amount of trust than what is usual.

5.4. ON INSURANCE

It has been suggested that insurance could be employed as one of the means of implementing the precautionary principle[222]. However, while insurance is of great value in many settings, one can nevertheless argue that insurance *alone* is insufficient for the operationalisation of the precautionary principle:

1. The large-scale deployment of insurance contracts is likely to offer a sustainable solution only if the underwriters are capable of assessing harmful consequences and their probabilities. In the presence of scientific uncertainties, neither one is truly possible (i.e., decision trees cannot be deployed in order to

[221] Cf. Rogers (1999).

[222] See also Costenza and Cornwell (1992).

set premiums). It is true that some insurers (such as Lloyds') do provide insurance for exotic phenomena, but this is the exception rather than the rule.

2. When the consequences are very uncertain and the stakes high, the underwriters may simply decline to provide insurance. For example, insurance companies have presumably been unwilling to provide insurance for the transport of nuclear waste from Germany to the U.K. In fact, this (i.e., failure of the marketplace to cover risks) can be interpreted as an indication of a decision context in which the application of the precautionary principle is potentially warranted.

3. If the 'disaster' that was thought impossible does happen, underwriters may default due to the many claims they will be inundated with. This is not in anybody's interest[223].

This is not to say that insurance might not be a viable option in some contexts. In fact, insurance provides extremely useful tools for managing hazards that can be anticipated with some degree of confidence.

6. ASSESSMENT OF DECISION ANALYSIS

The discussion of decision analysis in the previous sections illustrates some of the properties that are characteristic of formal modelling approaches. Typically, these properties vary considerably depending on the problem and the approach that is adopted; value trees, for example, place more emphasis on the explication of the stakeholders' value concerns whereas decision trees clarify dependencies between chance events and successive decisions. Thus, there are complementaries that can be harnessed by combining elements of several approaches, even though the increased complexity of the analysis may lead to loss of transparency in the communication of results (see, e.g., Gray 1996).

The potential of decision analytic approaches is perhaps greatest in risk management and, specifically, in supporting choices between value-laden regulatory options. For the earlier phases of risk identification and evaluation, other approaches –such as the use of checklists and flowcharts – may are more suitable[224]. That is, these earlier phases supply science-based results, whereas decision analysis provides tools explicating what these results signify in conjunction with the stakeholders' interests and value concerns (cf. US 1997).

While decision analytic representations provide support for policy making, they can also be deployed in a more exploratory sense where the purpose is to clarify the potential impacts of new technology. The aim of such uses is not so much to arrive at a "solution", but to support the debate in the course of which the relevant concerns are explored (see, e.g., Hämäläinen 1990). Examples of representations built for this purpose include the multi-criteria mapping approach of Stirling (1997) and the rank-based approach to comparative risk analysis by Kadvany (1985).

The conclusions supported by decision analytic modelling depend on 1) the framing of the problem and 2) the numeric values of key parameters. Since each model is essentially a reflection of the perspective that has been adopted in formulating the problem, it is likely that different models will be regarded as more or less 'valid' by different stakeholders. The implication of this is that it might be beneficial to pursue several methodological approaches in parallel, as this may provide further insights and place the results into a more encompassing perspective.

Another facet in the assessment of decision analytic modelling is that the models feed into the power plays that are pervasive in policy making. To acknowlegde the diversity of interests at stake, it may be pertinent to carry out separate analyses for each of the stakeholders, especially if there is little chance of developing a commonly accepted framework. The key benefit of these separate analyses is that they 1) explicate the concerns that matter to the different stakeholders most and 2) expose the issues where disagreements are largest. At best, such exploratory uses of decision analysis clarify how the problem is perceived and suggest directions where common ground may be gained[225].

[223] See Fleming (1996).

[224] See, e.g., Gray (1996), Mee (1996)

[225] See, e.g., Stirling and Mayer (1999).

Although multi-criteria decision analysis does hold promise for the management of technological risks, its potential is nevertheless bounded by factors which relate to 1) the incompleteness of knowledge, partly due to scientific uncertainties, 2) methodological foundations, which constrain the types of models that can be justified, and 3) potential difficulties in deploying decision analytic models as tools for the support of social debate and deliberation. Specifically, we draw attention to the following remarks:

1. *Comprehensiveness and completeness of the modelling endeavour:* While decision analytic models are flexible enough to accommodate a wider range of concerns than, say, cost-benefit analyses, it is nevertheless impossible to ascertain *in advance* that all the relevant concerns have been captured. Indeed, in situations characterised by ignorance and indeterminacy, technology may provoke unanticipated environmental effects that give rise to totally new value concerns. These problems are caused not so much by failures in modelling methodology but, rather, by the inability to even approach issues which, by the very definition of ignorance, escape recognition.

2. *Validity of underlying theoretical assumptions:* Decision analytic models are premised on rather stringent assumptions about the structure of the decision makers' preferences. For example, the additive value models assume that the decision maker's preferences fulfil the condition of mutual preferential independence (i.e., the decision maker's preferences for consequences on one attribute must be independent of his or her preferences with respect to the other attributes). In environmental decision problems, however, it is conceivable that this assumption fails to hold: for instance, some criteria (e.g., economic growth) may become relevant only when consequences with regard to other criteria (e.g., health) are acceptable.

3. *Characterisation of alternatives:* Much of the literature on decision analysis is concerned with how a rational decision maker (i.e., one who acts in accordance with the axioms of rationality) would choose among distinct, well-defined alternatives. In the shaping of regulatory policies, such alternatives are not available at the outset, but – rather – they evolve through negotiations between the regulator and the stakeholders. Indeed, the creation of acceptable alternatives is a many-faceted problem with complex interfaces to other realms of regulatory policy, commitments of current and future resources and conflicts over the distribution of institutional power.

4. *Knowledge of stakeholders' preferences:* The construction of decision analytic models presumes that the stakeholders are willing to reveal their 'true' preferences. However, in view of the antagonistic character of the debates on controversial technologies, it would be unrealistic to assume that the stakeholders are automatically willing to 'reveal their cards', as they might sacrifice their negotiation position by doing so. Th ere is consequently a need to institute decision making procedures that are open and simple enough to evoke trust and, at the same time, enact incentives against wilful misrepresentation of preferences.

5. *Causation and temporal uncertainties (in structure).* While value trees are helpful in conveying value positions, they are nevertheless not flexible in terms of capturing temporal interactions between technology and its environment, or the effect that such interactions have on later contingencies. To de scribe these interactions, more elaborate approaches are needed, even though the adoption these approaches is likely to detract from the transparency of the modelling endeavour. Thus, there is an inherent tension between realism and simplicity, which, in the name of accessibility, might be resolved to the benefit of the latter.

6. *Availability of computer support.* The methods that are capable of simultaneous sensitivity analyses call for the use of dedicated software tools. At present, such software is not widely available, although some pilot packages have been developed [iii].

7. *Methodological awareness.* The application of formal analysis presumes that the stakeholders are at least somewhat familiar with the methods and tools. There is therefore a need to train and educate them at the same time when there is a need to limit the level of sophistication of the approaches.

8. *Acceptance of methodologies.* The widespread use of decision analytic tools in risk management would shift the discourse into a more structured framework and, by doing so, affect the stakeholders' negotiation positions. In consequence, the stakeholders whose position might weaken as a result of such a shift may be opposed to any 'methodological advances'.

7. QUALITATIVE STRATEGIC FACTORS

In this project, several concepts related to the systemic behaviour arising from the interactions between technology, environment and the regulatory system have been found relevant to the management of technological risks. In particular, the notions of r*obustness, flexibility, resilience, adaptability, persistence, reversibility, ubiquity* and *locality* have surfaced repeatedly.

In what follows, we seek to clarify these concepts within a decision analytic framework. This task, however, is not easy because the literature does not, to our knowledge, contain widely accepted definitions for these terms. We therefore draw upon related definitions from the terminology on systems theory and use these to interpret these concepts.

Three immediate observations can be made about these concepts. First, they refer to dynamic properties that characterise changing interrelationships between the social, economic, environmental and technological dimensions. Second, many of these concepts may be viewed either from the perspective of the environment (e.g., 'How does environment adapt to the release of some chemical?') or the regulatory system (e.g., 'How does the regulatory system adapt to new scientific knowledge on the environmental impacts of this chemical?').

A provisional distinction between these concepts can be made along the axes of 1) deliberate choice, 2) mode of response to perturbations and 3) permanence of effects. Specifically:

- Robustness and flexibility are attributes of strategies that have been adopted in order to prepare for future uncertainties. This notion is in keeping with the use of these terms in scenario analysis and resource planning, for instance[226].
- Resilience and adaptability, on the other hand, refer to alternative modes of persevering under external perturbations, of which the introduction of potentially harmful technologies into the environment is but an example.
- Persistence and reversibility refer to the permanence of impacts associated with the introduction of technology, either in the presence or absence of policy measures.

The above concepts are neither exhaustive nor mutually exclusive. Yet, one could stress their differences by stating that either robust or flexible strategies could be adopted, in order to reduce persistent or reversible effects, associated with the resilience or adaptability exhibited by the environment in its response to the introduction of technology. We next discus s each of these concepts in some more detail.

7.1 ROBUSTNESS AND FLEXIBILITY

Robustness and flexibility can be regarded as alternative strategies for preparing for future uncertainties. Specifically, robustness characterises strategies that are expected to perform satisfactorily under all the envisaged future conditions.[227]Flexibility, in contrast, refers to the selection of strategies that minimise current commitments and seek to identify and exploit possibilities for subsequent adjustments, in response to the information that will be obtained later. In this sense, flexibility is related to the "step-by-step"-principle, according to which advances in the use of technology are taken gradually, in the understanding that the steps taken provide more information.

The adoption of robustness as a guiding principle, therefore, implies that strategies with a satisfactory performance in the worst-case scenario will be given priority over others. Flexibility, on the other hand, seeks to defer irrevocable decisions and gives precedence to an active search for new options and alternatives.

[226] See Andrews (1995).

[227] Andrews (1995).

While the delineation between robustness and flexibility is subject to interpretation, both these strategies are problematic in the context of large scientific uncertainties:

1. To the extent that scientific uncertainties make it impossible to construct a comprehensive set of future scenarios (and worst-case scenarios in particular), the shaping of truly robust strategies will be difficult.
2. The implementation of flexibility, as an operational strategy, requires that the policy process is able to continually acquire further information and capable of rapidly translating it into policy action.

7.2 RESILIENCE AND ADAPTABILITY

In the context of technical systems, resilience refers to the ability of the system to sustain its essential performance characteristics when subjected to external perturbations. Adaptability, on the other hand, denotes the ability of the system to alter its structural or functional properties in such way that it remains a viable functioning entity (with possibly altered performance characteristics, however).

7.3 Persistence and Reversibility

Persistence and reversibility can be understood as temporal attributes of the environmental impacts caused by the deployment of technology. That is, persistent impacts are likely to remain in effect over extended periods, whereas reversible impacts may disappear, either due to policy measures or spontaneous processes of adaptation. Both of these attributes can be considered either in conjunction with or in the absence of regulatory measures.

7.4 ASSESSMENT OF MANAGEMENT STRATEGIES

At best, the consideration of qualitative strategic factors support the design of appropriate risk management strategies[228]. In addition to the ones listed above, these factors can be extended to dimensions such as scope of geographical coverage, immediacy of occurrence, severity of harm and certainty of detection.

A possibility in harnessing qualitative factors in risk management is to employ them as axes of a multidimensional space where the precautionary principle is invoked under certain combinations of these factors (e.g., severity & irreversibility & incertitude). Such a positioning provides a framework for the assessment of alternative policy measures and, in particular, for the design of strategies aimed at transforming the regulatory problem into one where less reliance on precaution is called for. In this sense, the taxonomy of risk management strategies proposed by of Renn and Klinke (1999) can be regarded as an extension of the work of Deville and Harding (1997) whose typology covers the dimensions of irreversibility and scientific uncertainty only.

From the perspective of strengthening the use of these factors in regulatory decision making, there is a challenge in defining them in *measurable* terms for the handling of individual cases. For example, while the general meaning of 'reversibility' is relatively clear, its practical use immediately raises questions such as how *quickly*, *surely*, *at what cost* and *under what conditions* the impacts should be reversible. Here, some of the other notions (such as 'adaptability' and 'resilience') are even more challenging in that the 'end state' which is to be reached is not defined at the outset.

A potential problem with strategic qualitative factors is that their use (say, in promoting flexible, open-ended strategies) presumes that these factors correctly characterise how the environment responds to releases of hazardous substances or the policy measures that are intended to counter or reverse harmful impacts. Yet, it is conceivable that, under conditions of indeterminacy or ignorance, the harm that was thought to be 'reversible' in the light of small-scale experiments cannot be reversed after the technology has been deployed on a large scale. Thus, the characterisation of these factors may *in itself* be subject to errors, much in the same way as attempts to produce accurate predictions for the long-term impacts of environmental releases.

[228] See, e.g., Renn and Klinke (1999).

7.5 Levels of Analysis

In the shaping of regulatory policies, it is helpful to distinguish between different levels of analysis. First, there is the 'strategic' level concerned with the choice of principles and procedures that shape the formation of policies that are applied to individual cases (e.g., product notifications). Second, there is the 'operational' level concerned with the application of these policies to the cases that are submitted to the national and EU authorities.

The uncertainties are perhaps greatest at the strategic level because, in order to itemise principles of risk analysis, the regulator would have to anticipate the full range of applications and their associated impacts, which is impossible in areas where there are considerable scientific uncertainties. To avoid this difficulty, the details can be relegated to the operational procedures and, specifically, to the requirement that the decisions are to be taken in the light of most recent knowledge. But this, then, involves the possibility that different authorities will interpret the legislation differently, and that the *de facto* implementation is disassociated from the very principles which the regulator had initially in mind[229].

Herein is one of the challenges for the operationalisation of the precautionary principle. That is, what processes and methodological tools (in the broad sense) should be employed, in order to ensure that the operationalisation remains aligned with the objectives of legislation and, at the same time, compatible with requirements for democratically responsible decision making.

8. DIMENSIONS OF QUALITY

In addressing the quality of attempts to operationalise the precautionary principle, it is helpful to make a distinction between the following dimensions:

1. The quality of the modelling efforts (e.g., comprehensiveness, completeness, consistency).
2. The participatory elements of the decision making process (e.g., accessibility, communicability, openness).
3. The *ex post* quality of the decisions taken (e.g., were the decisions 'right' in hindsight?).

The following remarks exemplify some of the quality-related characteristics:

1. *Comprehensiveness, completeness, consistency*. Comprehensiveness refers to the requirement to contain all the relevant impacts in the analysis (i.e., 'breadth'), while completeness refers to the need to cover these impacts in sufficient detail (i.e., 'depth'). Consistency, on the other hand, implies that the construction of models should be compatible with the requirements posed by the underlying theoretical framework[230].
2. *Recognition of inherent limitations.* Most economic forecasts are predicated on the tacit assumption that no *force majeure* disruptions (e.g., major catastrophes) occur over the forecast period while often no mention is made of the less obvious assumptions on which the forecasts are based. Nevertheless, care should be taken to explicate the factors which might invalidate the analysis (even if *ignorance* limits the extent to which such an attempt can succeed).
3. *Stakeholder involvement.* Since the regulation and management of consequential technologies is a political matter, procedures for involving different stakeholders are worth promoting. Participatory approaches such as consensus conferences have already proven themselves productive and operationally feasible.[231]

[229] Cf. the discussion of Shohet (1996) on Directive 90/220/EEC.

[230] See Bunn and Salo (1993) for a discussion on the quality of scenarios.

[231] Cf. Durant and Joss (1995).

4. *Accessibility* . A prerequisite for stakeholder involvement is that the decision process is *accessible*. In other words, the essentials at stake should be 1) communicated to any interested and affected parties and 2) described in documents that can be understood by educated laymen; for example, these documents should contain summaries that are free of technical jargon.

5. *Predictability.* A plausible requirement is that the process through which the decision will be reached is predictable, not necessarily so much in its outcome, but in its structure and possibly in its duration as well. For example, the Directive 90/220/EEC has been criticised because the comitology procedure of Article 21 does not limit the time that the Commission may take in submitting its proposal to the Council[232].

6. *Expediency.* The amount of effort spent in analysis and deliberation - as well as the precautionary measures themselves - should be commensurate with the importance that can be accorded to the potential benefits and harmful impacts of technology.

7. *Indisputability.* A source of potential conflict in the operationalisation of the precautionary principle is that no specific criteria have been laid down which would make it possible to assess *ex post* whether the principle has been 'correctly' applied. This being the case, decisions based on the precautionary principle can be disputed more easily than those which are based on the application of falsifiable scientific rules. There are, as a result challenges in terms of defining how strategic qualitative factors (e.g., reversibility) could be *measured*.

9. CONCLUSION

In this paper, we have considered the role of decision of analytic modelling in risk management and the operationalisation of the precautionary principle. Based on this discussion, it appears that decision analysis - and some of the recent methodological developments in particular –offer potentially useful analytical tools for the explication and communication of risks. This is because decision analytic modelling leads to a clear distinction between the different dimensions of uncertainties (i.e., scientific evidence, stakeholders ' value concerns, impact of policy options). The construction of these models also 1) conveys those dimensions with regard to which knowledge is deficient, incomplete or fragmentary and 2) illustrates how possible improvements in the knowledge basis would affect the results of the analysis.

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[232] See, e.g., Schomberg (1998).

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[i] For more realistic examples, we refer to Gray (1996) and references cited therein.
[ii] Complications may arise, however, if the stakeholders' value concerns change over time. If this is the case, the question arises whether the analysis should be based on current or anticipated value representations.
[iii] A recent assessment of some 32 software packages for decision analysis can be found in the 1998 August issue of *OR/MS Today*. Pilot tools capable of simultaneous sensitivity analyses have been developed at the Systems Analysis Laboratory in the Helsinki University of Technology (see *http://www.hut.fi/Units/SAL/Downloadables/*).